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Author(s)	白瀧, 浩志
Citation	大阪大学, 2019, 博士論文
Version Type	VoR
URL	https://doi.org/10.18910/72359
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Doctoral Dissertation

Studies on Ni(0)-Catalyzed Multi-Component Coupling Reactions with Tetrafluoroethylene via the Oxidative Cyclization

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January 2019

Graduate School of Engineering

Osaka University

Contents

Preface and Acknowledgement

The study in this thesis has been carried out under the direction of Professor Sensuke Ogoshi at the Department of Applied Chemistry, Faculty of Engineering, Osaka University from April 2014 to March 2019. The thesis describes Ni(0)-catalyzed multi-component transformations with tetrafluoroethylene via the oxidative cyclization as a key reaction step.

I would like to appreciate very much a number of suggestions and encouragement to Professor Sensuke Ogoshi. I would like to express my appreciation to Professor Naoto Chatani and Professor Toshiyuki Kida for their stimulating discussions. I would also like to express my special thanks to Associate Professor Masato Ohashi, Assistant Professor Yoichi Hoshimoto, Project Assistant Professor Kotaro Kikushima (Ritsumeikan University), Project Assistant Professor Kumar Ravindra (CSIR-Cental Drug Research Institute, India), and Project Assistant Professor Hazra Sunnit (Miura Laboratory, Osaka University) for their continuous guidance, advice, and assistance.

I would like to show my gratitude to Ms. Noriko Fujimoto and Ms. Chiaki Kawamura for their kind support and encouragement.

I am grateful to Mr. Takuya Kawashima, Mr. Takuya Kinoshita, and Ms. Yukari Sasaoka as peers in my master's course.

I am deeply indebted to my senior alumni in Ogoshi group, Dr. Akira Nishimura, Dr. Hiroki Saijo, Dr. Ryohei Doi, Dr. Yukari Hayashi, Mr. Tomoya Ohata, Mr. Seita Kimura, Mr. Mitsutoshi Shibara, Dr. Hironobu Sakaguchi, Ms. Eri Tamai, Mr. Hayato Yabuki, and Mr. Hiroaki Saito for their kind advice. I would like to express my thanks to my junior in Ogoshi group, Mr. Takahiro Asada, Mr. Takuya Adachi, Mr. Yuta Ueda, Mr. Kyogo Maeda, Mr. Akira Onishi, Mr. Keita Ashida, Mr. Naoyoshi Ishida, Mr. Takaya Hinogami, Mr. Kazuya Ishimoto, Mr. Ryohei Suzuki, Mr. Yasuhiro Yamauchi, Mr. Takafumi Ono, Mr. Kota Ando, Mr. Yu Hashimoto, Ms. Shiori Kusaka, Mr. Yugo Ueda, Ms. Tinghui Yu, Mr. Hiroto Imiya, Ms. Mahiro Sakuraba, Ms. Anna Shigaki, Ms. Chika Nishimura, Mr. Kodai Fukudome, Mr. Junu Kim, Mr. Hideki Ito, Mr. Wataru Sahashi, Mr. Nozomi Yasui, and Ms. Wafiya Inas for their helpful assistance and dedication.

I would like to express my special thanks to Dr. Nobuko Kanehisa for her helpful assistance for the X-ray diffraction analysis and to the Instrumental Analysis Center, Graduate School of Engineering, Osaka University for the measurement of spectral and analytical data.

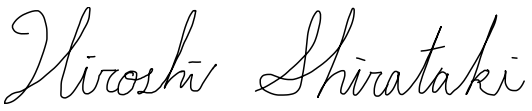
I am thankful to Daikin Industries, Ltd. for supplying tetrafluoroethylene throughout this study. I would particularly like to thank Dr. Takashi Shibanuma, Mr. Kenji Adachi, Dr. Takabumi Nagai, and Mr. Tadashi Kambara for their discussion and helpful support.

I acknowledge the scholarship from the Cross-Boundary Innovation Program and the Research Fellowship from the Japan Society for the Promotion of Science for Young Scientists.

My utmost gratitude is dedicated to my family, Ms. Atsuko Shirataki, Ms. Kayo Shirataki, Dr. Hiromichi Shirataki, Ms. Natsuko Shirataki, and Ms. Arisa Shirataki for their affectionate support and encouragement.

Finally, my appreciation cannot be expressed in words for all people who helped me in my Ph.D life.

January 2019



Hiroshi Shirataki

List of Abbreviations

Ac	acetyl
anal.	elemental analysis
Ar	aryl
atm	atmospheric pressure
Boc	*tert*-butoxycarbonyl
br	broad
Bu	butyl
calcd	calculated
cat.	catalyst
CI	chemical ionization
cod	1,5-cyclooctadiene
Cy	cyclohexyl
°C	degrees Celsius
d	doublet
d	deuterated
DABCO	1,4-diazabicyclo[2.2.2]octane
DCPB	1,4-bis(dicyclohexylphosphino)butane
DCPE	1,4-bis(dicyclohexylphosphino)ethane
Dipp	2,6-diisopropylphenyl
DPPB	1,4-bis(diphenylphosphino)butane
δ	chemical shift of NMR signal in ppm
η	eta
e.g.	for example
eq	equivalent
EI	electron ionization
Et	ethyl
ETFE	ethylene-tetrafluoroethylene copolymer
GC	gas chromatography
GWP_{100}	global warming potential
h	hour(s)
HPLC	high performance liquid chromatography

HRMS	high-resolution mass spectrometry
Hz	hertz
i	iso
ICy	1,3-dicyclohexylimidazol-2-ylidene
IMes	1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene
IPr	1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene
IPrCl	1,3-bis(2,6-diisopropylphenyl)-4,5-dichloro-imidazol-2-ylidene
I^{t}Bu	1,3-di-*tert*-butylimidazol-2-ylidene
J	coupling constant in NMR
L	ligand
LDA	lithium diisopropyl amide
m	multiplet
m	meta
min	minute(s)
mL	milliliter
M	metal
Me	methyl
Mes	Mesityl
n	normal
NHC	*N*-heterocyclic carbene
NMR	nuclear magnetic resonance
o	ortho
ORTEP	Oak Ridge thermal ellipsoid plot
p	para
Ph	phenyl
Phen	1,10-phenanthroline
pin	pinacolato
Pr	propyl
PTFE	poly-tetrafluoroethylene
q	quartet
quant	quantitative
rt	room temperature
s	singlet

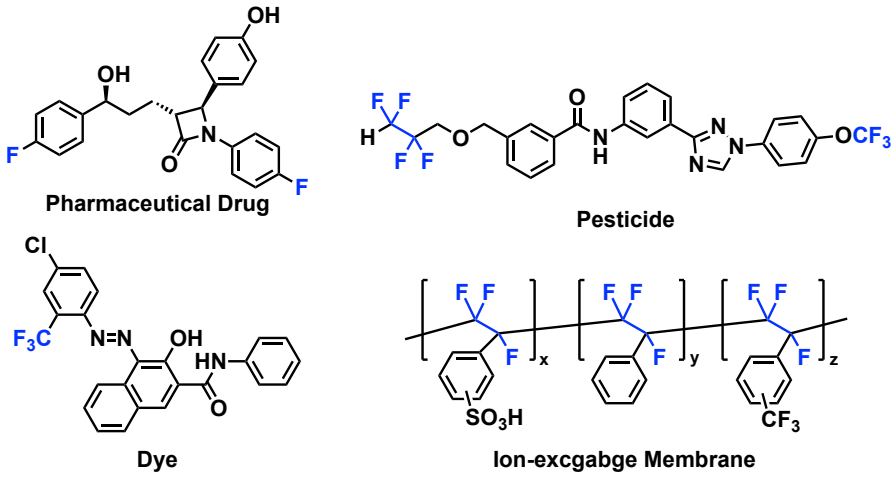
SIPr	1,3-bis(2,6-diisopropylphenyl)-4,5-dihydro-1*H*-imidazol-3-ium-2-ide
t	triplet
t	tertiary
temp	temperature
TFE	tetrafluoroethylene
THF	tetrahydrofuran
TMS	trimethylsilyl
tol	tolyl
TON	turnover number
triphos	1,1,1-tris(diphenylphosphinomethyl)ethane

Chapter 1
General Introduction

1.1 Organofluorine Compounds

Organofluorine compounds are widely used in physiologically active compounds (e.g. pharmaceuticals and agrichemicals) and functional materials (e.g. liquid crystals and solar cells)[1] owing to their unique features, which are predominantly due to the presence of the fluorine atom (Figure 1.1).[2] Thus, several synthetic routes to such compounds has been developed over the past few decades. For instance, the introduction of a fluorine atom into organic compounds using fluorination agents is a well-established approach.[3] However, it is unsuitable for the synthesis of highly fluorinated organic compounds due to i) the usually high cost of reagents and ii) the limited availability of suitable substrates. On the other hand, the transformation of industrially available perfluorinated compounds into a variety of highly fluorinated organic compounds is a more straightforward approach.[4]

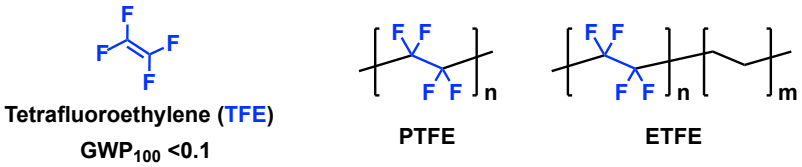
Figure 1.1. Representative Examples of Organofluorine Compounds.



1.2 Tetrafluoroethylene

Among such perfluorinated compounds, tetrafluoroethylene (TFE) is a virtually ideal starting material as it is an economical feedstock in the fluorine industry and environmentally friendly with a negligible global warming potential (Figure 1.2).[5] However, the conventional use of TFE has been limited mostly to the production of polytetrafluoroethylene (PTFE) and copolymers with other alkenes such as ethylene-TFE copolymer (ETFE).[6] Given these limitations, methods for the efficient transformation of TFE have been explored extensively.

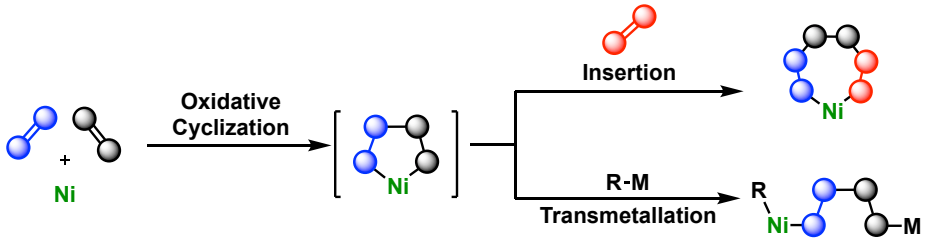
Figure 1.2. Tetrafluoroethylene as an Ideal Starting Material.



1.3 Oxidative Cyclizations with Ni(0) as a Key Reaction Step

In this thesis, the focus was placed on one such strategy: the transformation of TFE by Ni(0)-catalyzed reactions that involve an oxidative cyclization. Such oxidative cyclizations with Ni(0) can efficiently produce a nickelacycle under concomitant formation of a C–C bond between a variety of two π-components (Figure 1.3).[7] Furthermore, the thus obtained nickelacycles are susceptible to insertions of unsaturated compounds and transmetallations with organometallic reagents. Therefore, such nickelacycles may serve as key intermediates in multi-component coupling reactions.[8]

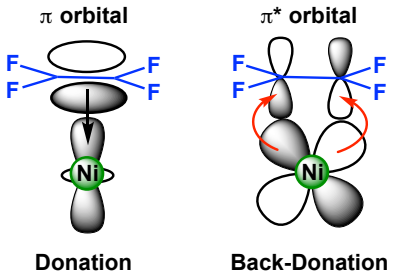
Figure 1.3. Ni(0)-Catalyzed Reactions via Oxidative Cyclizations.



1.4 The Coordination Ability of TFE to Ni(0)

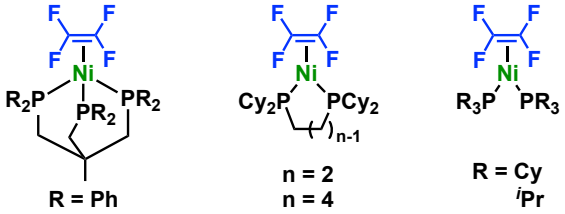
Prior to the aforementioned oxidative cyclization, two π-components have to coordinate to Ni(0). In this context, TFE can be regard as an excellent π-component, given that its coordination ability is strong due to the back-donation from Ni(0) (Figure 1.4).

Figure 1.4. Electron Donation and Back-Donation between Ni(0) and TFE.



This has been demonstrated by the synthesis of (η^2-TFE)Ni(0)L_n complexes coordinated by a tridentate phosphine ligand such as 1,1,1-tris(diphenylphosphinomethyl)ethane (triphos), bidentate phosphines such as 1,4-bis(dicyclohexylphosphino)ethane (DCPE) and 1,4-bis(dicyclohexylphosphino)butane (DCPB), as well as sterically demanding monodentate ligands such as PCy_3 and P^iPr_3 (Figure 1.5).[9]

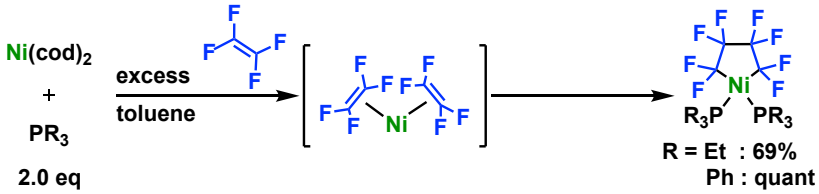
Figure 1.5. (η^2-TFE)Ni(0)L_n Complexes Coordinated by Phosphine Ligands.



1.5 Nickelacycles Generated from Two Molecules of TFE

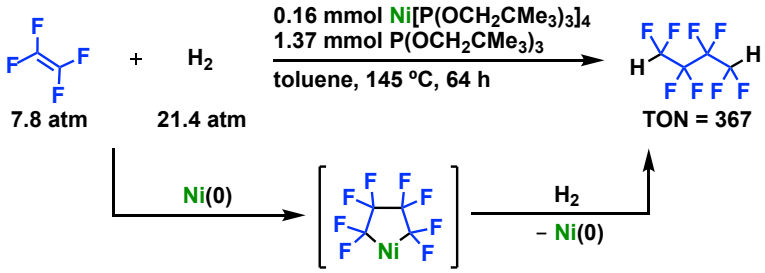
When the reaction of TFE and $Ni(cod)_2$ was conducted with PEt_3 or PPh_3, whose cone angles are relatively small, the oxidative cyclization of two molecules of TFE produced $(CF_2CF_2CF_2CF_2)Ni(PR_3)_2$ via the formation of a (η^2-TFE)$_2$Ni(0)L complex (Scheme 1.1).[10, 11]

Scheme 1.1. First Example of the Oxidative Cyclization of TFE.



A first catalytic reaction via such a nickelacycle, generated from the oxidative cyclization of two molecules of TFE was reported by the group of Baker in 2001. Specifically, the Ni(0)-catalyzed transformation of TFE and H_2 into 1,1,2,2,3,3,4,4-octafluorobutane (TON = 367) was reported (Scheme 1.2).[12]

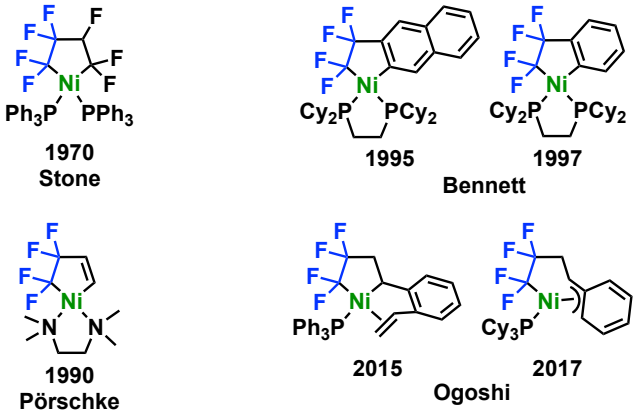
Scheme 1.2. A Catalytic Reaction via a Nickelacycle Generated from TFE.



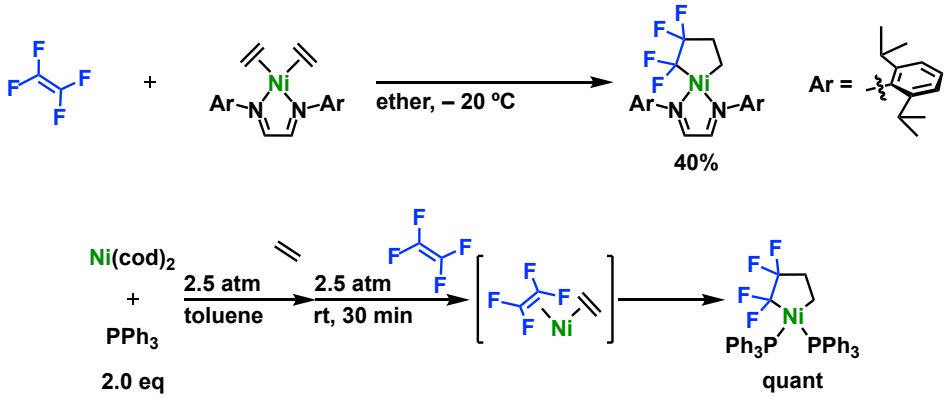
1.6 Nickelacycles Generated from TFE and Another π-Component

Oxidative cyclizations between TFE and another π-component, including alkynes and alkenes, that furnish the corresponding nickelacycles have also been reported (Figure 1.6).[12] For example, the oxidative cyclization of TFE and ethylene with Ni(0) and a ligand such as a diimine (Pörschke, 1991)[13c] or PPh_3 (Ogoshi, 2015)[11] produces a five-membered nickelacycle generated from TFE and ethylene (Scheme 1.3). In general, the oxidative cyclization between electron-rich and -deficient π-components on Ni(0) is kinetically much more favorable than those occurring between two electron-deficient π-components.[14] Thus, the oxidative cyclization of TFE and an electron-rich π-component can selectively produce the desired nickelacycles.

Figure 1.6. Nickelacycles Generated from TFE and Another π-Component.

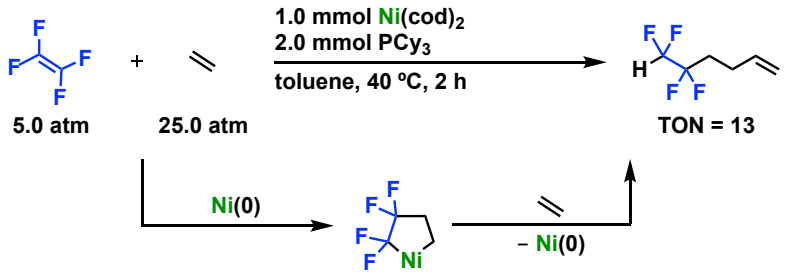


Scheme 1.3. Oxidative Cyclization of TFE and Ethylene with Ni(0).



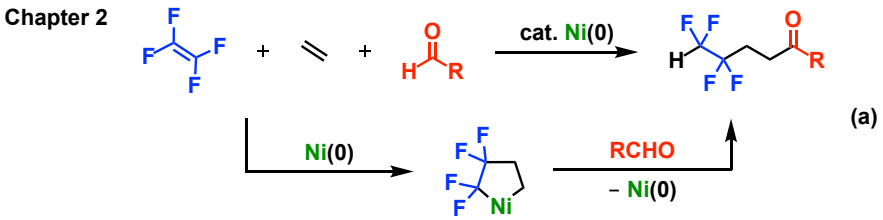
Our research group has reported catalytic oxidative cyclizations involving TFE and another π-component with Ni(0). For example, a Ni(0)-catalyzed co-trimerization reaction of TFE and ethylene afforded 5,5,6,6-tetrafluoro-1-hexene (TON = 13) (Scheme 1.4).[10] Mechanistic studies revealed that a five-membered nickelacycle generated from TFE and ethylene is the key intermediate for this catalytic reaction.

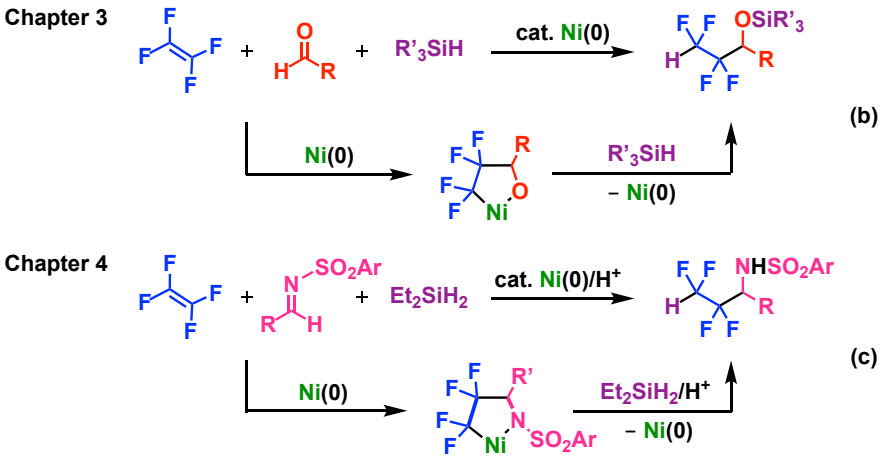
Scheme 1.4. Ni(0)-Catalyzed Co-Trimerization Reaction of TFE and Ethylene.



However, these Ni(0)-catalyzed reactions, which involve the oxidative cyclization of TFE and another π-component, had been limited to reactions between two different substrates. Against this background, we envisioned that this catalytic system could be developed to reactions between three different substrates, including TFE, for the synthesis of a variety of highly fluorinated compounds. Thus, the objective of this thesis was defined as the development of Ni(0)-catalyzed multi-component coupling reactions via the selective oxidative cyclization of TFE and another π-component such as ethylene, aldehydes, or imines (Scheme 1.5). This thesis consists of a general introduction (Chapter 1), three types of catalytic reactions (Chapter 2–4), and a conclusion. Each chapter (2–4) provides an introduction, a detailed results and discussion section, and a conclusion on the respective catalytic reactions: (i) a chemoselective Ni(0)-catalyzed cross-trimerization reaction of TFE, ethylene, and aldehydes (Chapter 2, Scheme 1.5a); (ii) a Ni(0)-catalyzed three-component coupling reaction of TFE and aldehydes with silanes via oxa-nickelacycles (Chapter 3, Scheme 1.5b); (iii) a Ni(0)-catalyzed three-component coupling reaction of TFE and *N*-sulfonyl-substituted imines with Et_2SiH_2 via aza-nickelacycles (Chapter 4, Scheme 1.5c).

Scheme 1.5. Ni(0)-Catalyzed Multi-Component Coupling Reactions of TFE and Other π-Components via the Oxidative Cyclization as the Key Reaction Step





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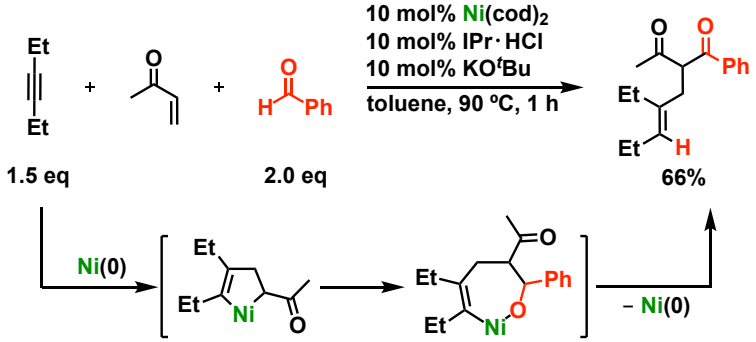
Chapter 2
Chemoselective Ni(0)-Catalyzed Cross-Trimerization Reaction of Tetrafluoroethylene, Ethylene, and Aldehydes

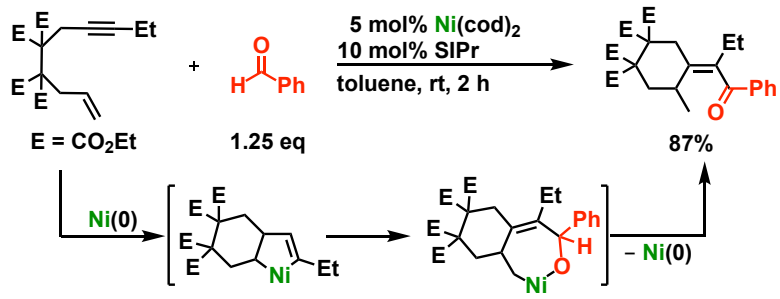
2.1 Introduction

Ni(0)-catalyzed multi-component coupling reactions have been studied so far as mentioned in the general introduction. For instance, Montgomery reported a chemoselective Ni(0)-catalyzed cross-trimerization reaction of alkynes, enones, and aldehydes (Scheme 2.1).[1a] In addition, Louie disclosed a Ni(0)-catalyzed intramolecular cross-trimerization reaction of alkynes, alkenes, and aldehydes.[1b] These catalytic reactions would proceed via the oxidative cyclization of alkynes and either enones or alkenes, followed by the insertion of aldehydes into the generated five-membered nickelacycles to furnish the target compounds. Based on this background, we investigated a Ni(0)-catalyzed cross-trimerization reaction via the oxidative cyclization of TFE and ethylene, followed by the insertion of aldehydes into the nickelacycle.

Scheme 2.1. Ni-Catalyzed Cross-Trimerization Reaction of Alkynes, Enones, and Aldehyde.



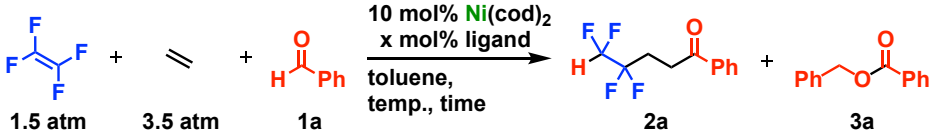
Scheme 2.2. Ni-Catalyzed Intramolecular Cross-Trimerization Reaction of Alkynes, Alkenes, and Aldehydes.



2.2 Optimization of the Reaction Conditions

The optimization of the reaction conditions for the Ni(0)-catalyzed cross-trimerization reaction of TFE, ethylene, and aldehydes was performed (Table 2.1). When a toluene solution of benzaldehyde (**1a**, 0.10 mmol) was exposed to ethylene (partial pressure = 3.5 atm) and TFE (partial pressure = 1.5 atm) at 40 ºC for 10 h in the presence of $Ni(cod)_2$ (0.010 mmol) and PCy_3 (0.020 mmol), 4,4,5,5-tetrafluoro-1-phenylpentan-1-one (**2a**) was furnished in 32% yield (entry 1). In this reaction, benzyl benzoate (**3a**), which was generated via a Ni(0)-catalyzed home-Tishchenko reaction of **1a**, was formed as a by-product in 13% yield.[2] The use of PPh_3 afforded **2a** and **3a** in 12% and 4% yield, respectively, whereas P^nBu_3 hardly gave **2a** (entries 2 and 3). Neither bulky phosphine ligands ($P(o\text{-tol})_3$ and P^tBu_3) nor bidentate ligands (DCPB and DPPB) were effective for the catalytic reaction (entries 4–7). The reaction with NHC ligands such as IPr and IPrCl afforded **2a** in 45% and 43% yield, respectively, although **3a** was also detected (entries 8 and 9). The yield of **2a** was decreased in the reaction with SIPr and *N*-alkyl-substituted NHC ligands such as ICy and I^{t}Bu (entries 10–12). The effect of temperature was critical to the catalytic reaction. Both the yield of **2a** and the product ratio of **2a**/**3a** were drastically improved as the reaction temperature was raised (entries 13–15). Elevating the reaction temperature to 150 °C furnished the desired product **2a** in 95% yield within 10 min (entry 15). In this catalytic reaction, a potential side product 5,5,6,6-tetrafluoro-1-hexene, which is a co-trimerization reaction product of TFE and ethylene,[3] was not detected by ^{19}F NMR analysis of the crude reaction mixture. Although employing PCy_3 and PPh_3 under the same reaction conditions accelerated the catalytic reaction to furnish **2a** in 48% and 22% yield, respectively, the yield and the product selectivity were inferior to that of IPr (entries 16 and 17). A reduction in catalyst loading (5 mol % of Ni(0)/IPr) did not affect the yield and the selectivity of **2a,** whereas a 2 mol% catalyst loading retarded the reaction (entries 18 and 19). The product **2a** was not formed in the absence of either IPr or $Ni(cod)_2$ (entries 20 and 21). These results revealed that both $Ni(cod)_2$ and IPr were essential for the Ni(0)-catalyzed cross-trimerization reaction. Thus, the optimal reaction conditions were determined as shown in entry 18. In addition, when the reaction mixture was prepared by the exposure of TFE and ethylene in this order under the optimal reaction conditions, the target compound **2a** was not generated since the reaction between TFE and IPr proceeded.[4] Therefore, it is important to pressurize TFE under the conditions that IPr does not dissociate from Ni(0) complexes.

Table 2.1. Optimization of the Reaction Conditions for the Ni(0)-Catalyzed Cross-Trimerization Reaction of TFE, Ethylene, and 1a.



Entry	Ligand	(x)	Temp. (°C)	Time (h)	Yield (%) 2a	3a
1	PCy_3	(20)	40	10	32	13
2	PPh_3	(10)	40	10	12	4
3	P^nBu_3	(10)	40	10	<1	<1
4	$P(o\text{-tol})_3$	(20)	40	10	0	0
5	P^tBu_3	(10)	40	10	0	3
6	DCPB	(10)	40	10	0	0
7	DPPB	(10)	40	10	0	0
8	IPr	(10)	40	10	45	28
9	IPrCl	(10)	40	10	43	30
10	SIPr	(20)	40	10	18	37
11	ICy	(10)	40	10	0	0
12	I^tBu	(10)	40	10	0	0
13	IPr	(10)	80	3	63	12
14	IPr	(10)	120	3	89	5
15	IPr	(10)	150	0.17	95	4
16	PCy_3	(20)	150	1	48	24
17	PPh_3	(10)	150	1	22	2
18[a]	IPr	(5)	150	0.5	98	4
19[b]	IPr	(2)	150	0.5	4	<1
20	none	(5)	150	0.5	0	0
21[c]	IPr	(5)	150	0.5	0	0

[a] Run with 5 mol% of $Ni(cod)_2$. [b] Run with 2 mol% $Ni(cod)_2$. [c] Run without $Ni(cod)_2$.

2.3 Substrate Scope

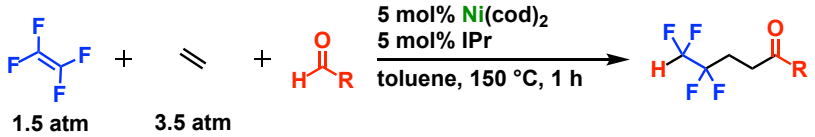
With the optimal reaction conditions, the scope and limitations of the Ni(0)-catalyzed cross-trimerization reaction with respect to various aldehydes were studied (Table 2.2). The Ni(0)/IPr system catalyzed the reaction of TFE, ethylene, and **1a** to afford **2a** in 80% isolated yield. The use of *p*-tolualdehyde (**1b**) and *m*-tolualdehyde (**1c**) afforded the corresponding target compounds (**2b** and **2c**) in 86% and 74% yield, respectively. Employing *o*-tolualdehyde (**1d**) diminished the yield (62%) of the target compound (**2d)** due to the generation of the undesired ester (**3d**). The reaction with mesitylaldehyde (**1e**) was sluggish on account of its excess bulkiness and generated a small amount of the target compound (**2e**). The use of *p*-fluorobenzaldehyde (**1f**) furnished **2f** in 71% yield, while neither *p*-chlorobenzaldehyde (**1g**) nor *p*-bromobenzaldehyde (**1h**) generated the desired products due to an undesired oxidative addition of Ni(0) into either a C–Cl or C–Br bond. Employing electron-donating group substituted aldehyde, *p*-anisaldehyde (**1i**), resulted in

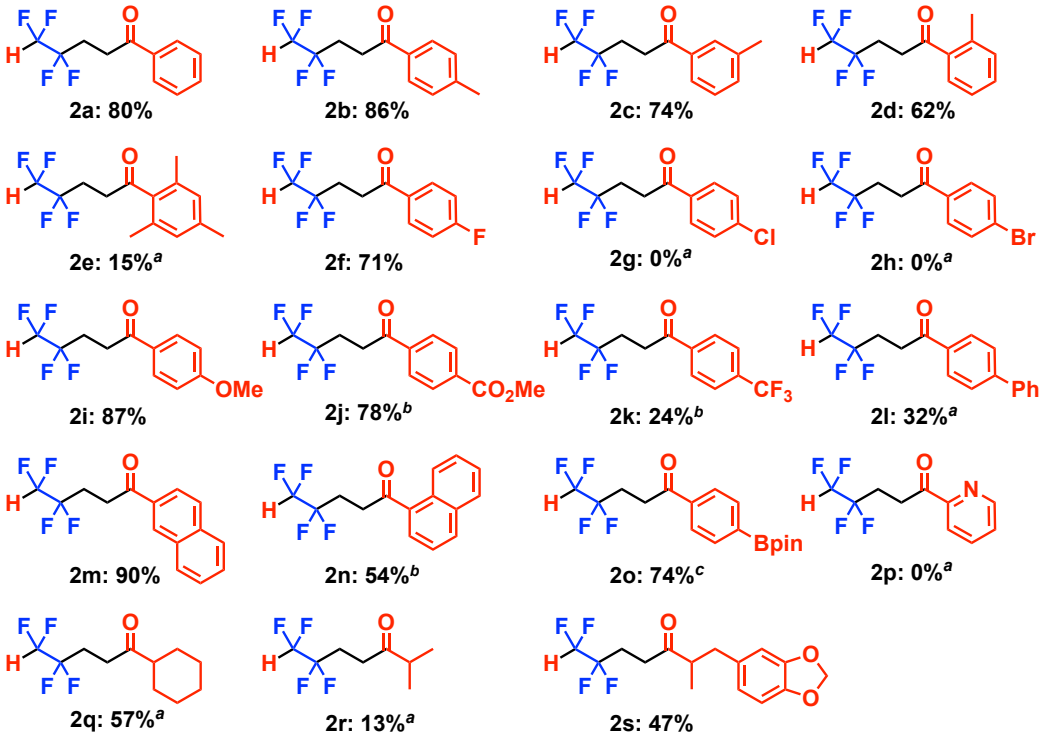
the formation of the target compound (**2i**) in 87% yield. The reaction with electron-withdrawing group substituted aldehydes such as methyl 4-formylbenzoate (**1j**) and *p*-trifluoromethylbenzaldehyde (**1k**) afforded the corresponding target compounds (**2j** and **2k**) in 78% and 24% yield in the presence of 10 mol% of $Ni(cod)_2$ and IPr for 24 h. The use of biphenylaldehyde (**1l**) furnished the target compound (**2l)** in 32% yield, which was detected by ^{19}F NMR analysis of the crude reaction mixture. 2-naphthaldehydes (**1g**) was tolerated to the reaction to produce **2g** in 90% yield. Employing sterically hindered 1-naphthaldehydes (**1h**) generated **2h** in 54% yield in the presence of 10 mol% $Ni(cod)_2$ and IPr. The reaction with *p*-boronate substituted benzaldehyde (**1m**) in the presence of 10 mol% of $Ni(cod)_2$ and IPr for 3 h afforded the target compound (**2m**) in 74% yield, which could be further used in a cross-coupling reaction. 2-pyridyl aldehyde (**1p**) was not tolerated for the reaction due to the deactivation of the nickel catalyst. The reactions with aliphatic aldehydes, cyclohexanecaroxaldehyde (**1q**) or 2-butanal (**1r**), furnished the corresponding compound (**2q** and **2r)** in 57% and 13% yield, respectively, which were detected by ^{19}F NMR analysis. The use of 3-(benzodioxol-5-yl)-2-methylpropanal (**1s**) afforded **2s** in 47% yield.

Subsequently, the Ni(0)-catalyzed cross-trimerization reaction was conducted with other alkenes instead of ethylene under the optimal reaction conditions (Scheme 2.3). Employing 1-hexene, however, did not afford the estimated target compound. The reaction with styrene also did not furnish the target compound although the oxidative cyclization of TFE and styrene with Ni(0) was reported to produce the corresponding η^3 nickelacycle.[5] This might be due to the weaker coordinating ability of 1-hexene and styrene than that of TFE and ethylene. Hence, the simultaneous coordination of TFE and either 1-hexene or styrene with Ni(0) and the following oxidative cyclization could not proceed.

The substrate scope of the catalytic reaction with respect to ketones instead of aldehydes was also examined under the optimal reaction conditions (Scheme 2.4). However, the reactions with cyclobutanone and trifluoroacetophenone afforded no target compound. In the case of the use of trifluoroacetophenone, a Ni(0)-catalyzed co-trimerization reaction of trifluoroacetophenone and two molecules of ethylene proceeded to furnish a trace amount of 1,1,1-trifluoro-2-phenylhex-5-en-2-ol.

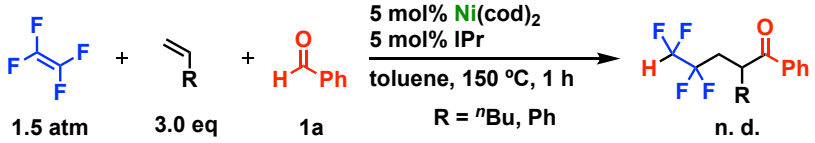
Table 2.2. Substrate Scope with respect to Aldehydes.



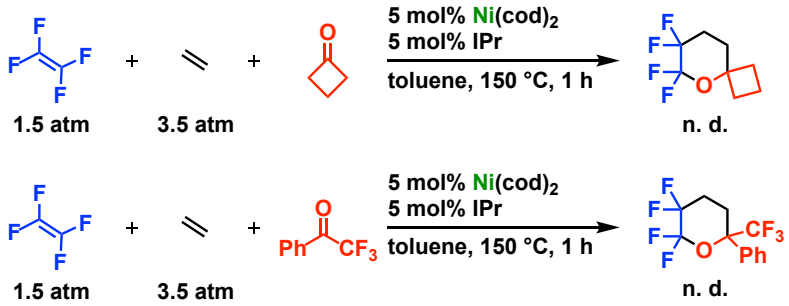


[a] Yield estimated by ^{19}F NMR analysis. [b] Run for 24 h with 10 mol% Ni(cod)$_2$/IPr.
[c] Run for 3 h with 10 mol% Ni(cod)$_2$/IPr.

Scheme 2.3. Substrate Scope with respect to Alkenes.



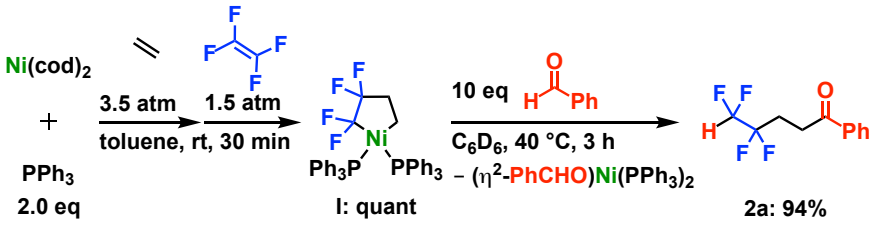
Scheme 2.4. Substrate Scope with respect to Ketones.



2.4 Stoichiometric Reactions

In order to gain deeper insight into the reaction mechanism, stoichiometric reactions were conducted (Scheme 2.5). A toluene solution of $Ni(cod)_2$ and PPh_3 was exposed to ethylene and TFE in this order. The reaction mixture was stirred at room temperature for 30 min to produce a five-membered nickelacycle (**I**) generated from TFE and ethylene quantitatively. The molecular structure of **I** has been confirmed by single-crystal X-ray diffraction analysis in our previous work.[3] The reaction of **I** with an excess amount of **1a** in C_6D_6 at 40 ºC for 3 h furnished **2a** in 94% yield. The resultant Ni(0) was trapped by **1a** and led to the quantitative formation of (η^2-PhCHO)$Ni(PPh_3)_2$. Thus, the catalytic reaction would proceed via a five-membered nickelacycle generated via the oxidative cyclization of TFE and ethylene with Ni(0). The isolation of the assumed five-membered nickelacycle key intermediate ligated by IPr was unsuccessful due to the formation of a seven-membered nickelacycle (**II**) generated from two molecules of TFE and one molecule of ethylene in 70% isolated yield (Scheme 2.6). Its molecular structure was confirmed by single-crystal X-ray diffraction analysis (Figure 2.1). The assumed five-membered ligated by IPr might be too transient to be observed even under strictly controlled conditions with respect to the TFE/ethylene ratio. The reaction of **II** with an excess amount of **1a** in toluene-d_8 at 150 ºC for 1 h afforded neither **2a** nor **3a**, which revealed that the nickelacycle **II** was not involving in the catalytic cycle.

Scheme 2.5. Stoichiometric Reactions with a five-membered Nickelacycle (I).



Scheme 2.6. Stoichiometric Reactions with a seven-membered Nickelacycle (II).

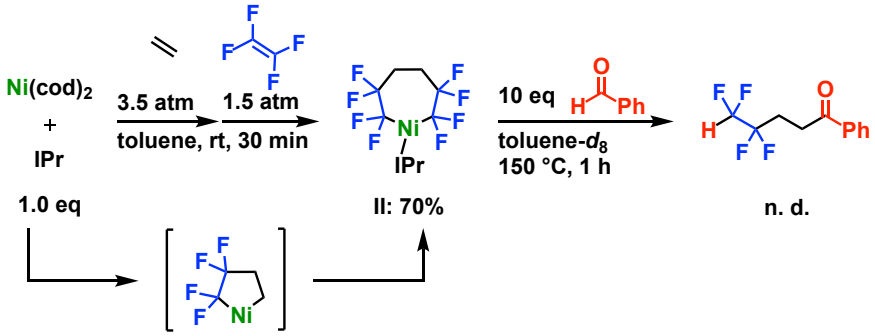
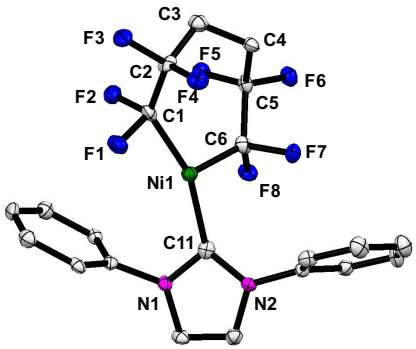


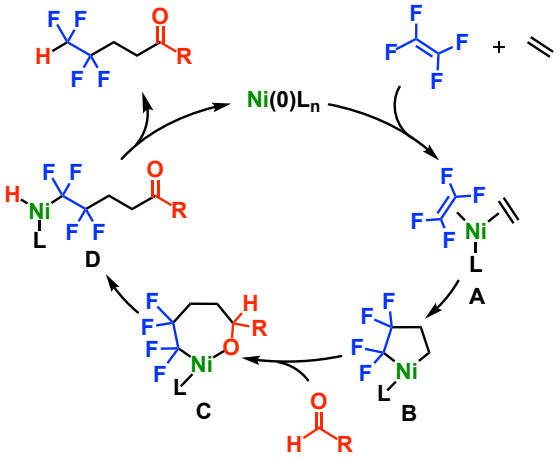
Figure 2.1. ORTEP representation of II with thermal ellipsoids at the 30% probability level. One of the crystallographically independent molecules in the unit cell has been depicted. Hydrogen atoms have been omitted for clarity.



2.5 Plausible Reaction Mechanism

On the basis of these results, a plausible reaction mechanism was shown in Scheme 2.7.[1, 3, 6] A simultaneous coordination of TFE and ethylene to Ni(0) generates η^2:η^2 nickel complex (**A**). Then, an oxidative cyclization produces a five-membered nickelacycle (**B**) as a key intermediate. An insertion of aldehydes into the Ni–CH_2 bond of **B** forms a seven-membered oxa-nickelacycle (**C**). Subsequently, a nickel hydride intermediate (**D**) is generated via β-hydride elimination from **C**. Finally, a reductive elimination proceeds to afford 4,4,5,5-tetrafluoro-1-pentanone derivatives along with a regeneration of the Ni(0) species. Although a catalytic cycle involving the oxidative cyclization of ethylene and aldehydes with Ni(0) is also considerable, it was unlikely based on the generation of (η^2-ethylene)$_2$Ni(IPr), which observed by ^{1}H NMR analysis when the catalytic reaction was monitored prior to the pressurization of TFE.[7]

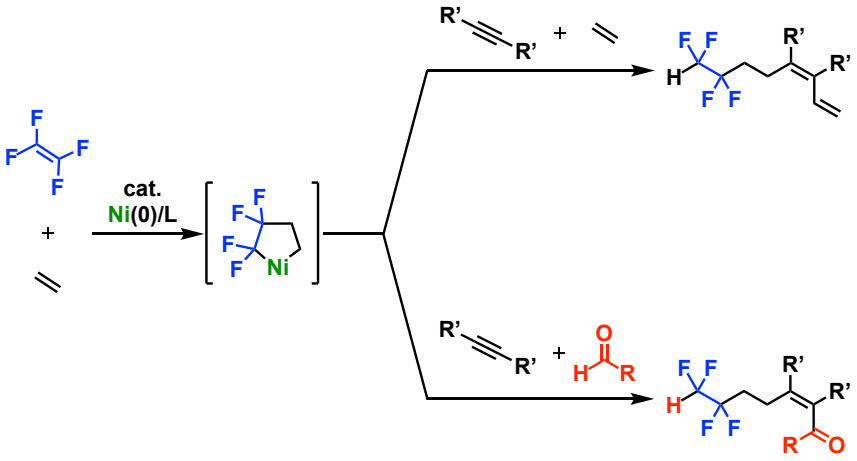
Scheme 2.7. Plausible Reaction Mechanism.



2.6 Our Related Works

Our research group has reported a Ni(0)-catalyzed tetramerization reaction of TFE, ethylene, and alkynes and a cross-tetramerization reaction of TFE, ethylene, alkynes, and aldehydes after this work.[8] The key to the successful development of such chemo- and regioselective cross-tetramerization is a sophisticated combination of TFE and ethylene for the oxidative cyclization with Ni(0) (Scheme 2.8).

Scheme 2.8. Our Related Works.



2.7 Conclusion

In Chapter 2, the Ni(0)/IPr system catalyzes a chemoselective cross-trimerization reaction of TFE, ethylene, and aldehydes to afford a variety of fluorine-containing ketone derivatives. Based on the results of mechanistic studies, a five-membered nickelacycle generated from TFE and ethylene is a key intermediate in the present catalytic reaction. In addition, a combination of TFE and ethylene, which is electron-deficient and -rich π-components, is crucial for the selective oxidative cyclization of with Ni(0).

2.8 Experimental Section

General statements for all experiments conducted in this thesis: All manipulations were conducted under a nitrogen atmosphere using standard Schlenk or dry box techniques. ^{1}H, ^{11}B, ^{13}C, ^{19}F, and ^{31}P NMR nuclear magnetic resonance (NMR) spectra were recorded on Bruker Avance III 400, JEOL AL-400, and Bruker Avance III 600 spectrometer at 25 °C unless otherwise noted. The chemical shifts in ^{1}H and ^{13}C NMR spectra were recorded relative to residual protonated solvent ($CHCl_3$ (δ 7.26 ppm for ^{1}H NMR and δ 77.16 ppm for ^{13}C NMR), C_6D_6 (δ 7.16 ppm for ^{1}H NMR and δ 128.06 ppm for ^{13}C NMR), and toluene-d_8 (δ 2.08 ppm for ^{1}H NMR and δ 20.43 ppm for ^{13}C NMR)). The chemical

shifts in ^{11}B NMR spectra were recorded to BF_3 as an external standard. The chemical shifts in ^{19}F NMR spectra were recorded relative to α,α,α-trifluorotoluene (δ –65.4 ppm) as an internal standard. The chemical shifts in ^{31}P NMR spectra were recorded using 85% H_3PO_4 as an external standard. Analytical gas chromatography (GC) was carried out on a Shimadzu GC-2014 gas chromatography or GC-2025 gas chromatography, equipped with a flame ionization detector. High-resolution mass spectrometry (HRMS) was performed at Instrumental Analysis Center, Faculty of Engineering, Osaka University. Elemental analysis was performed at Instrumental Analysis Center, Faculty of Engineering, Osaka University. Melting points were determined on a Stanford Research Systems MPA100 OptiMelt automated melting point system. X-ray crystal data were collected with Rigaku R-AXIS RAPID and Rigaku XtaLAB P200 equipped with the imaging plate diffractometer and Rigaku XtaLAB Synergy equipped with the HyPix-6000HE detector. Recycling Preparative High Performance Liquid Chromatography (HPLC) was performed on Japan Analytical Industry LC9225NEXT equipped with JAIGEL-1H and JAIGEL-2H.

Materials: The degassed and distilled solvents (pentane and toluene-d_8) used in this thesis were commercially available. C_6D_6, benzene, hexane, THF, and toluene were distilled from sodium benzophenone ketyl. Other commercially available reagents were distilled and degassed prior to use. Tetrafluoroethylene (TFE) was supplied by Daikin Industries, Ltd. *N*-Heterocyclic carbenes (NHCs) were synthesized by the known procedures.[9, 10]

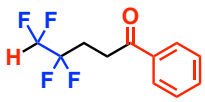
Caution: Tetrafluoroethylene (TFE) is suspected to be carcinogens. The reaction mixture must be handled in a well-ventilated fume hood

General procedure for the optimization of the reaction conditions: All reactions were conducted with a pressure-tight NMR tube (Wilmad-LabGlass, 524-PV-7). A toluene solution (0.6 mL) of $Ni(cod)_2$, ligand, and **1a** (0.10 mmol) was transferred into a pressure-tight NMR tube. Then, ethylene (3.5 atm, >0.30 mmol) and TFE (1.5 atm, >0.13 mmol) were charged in this order. The reaction mixture was heated at a given temperature. The yield of **2a** and **3a** were determined by gas chromatography using dodecane as the internal standard. The results of the optimization of the reaction conditions were summarized in Table 2.1.

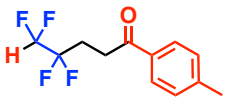
General procedure A for the substrate scope with the respect to aldehydes: A toluene solution (6.0 mL) of $Ni(cod)_2$ (13.8 mg, 0.05 mmol), IPr (19.4 mg, 0.05 mmol), and an aldehyde (**1**: 1.0 mmol)

was exposed to ethylene (3.5 atm) and TFE (1.5 atm) into an autoclave reactor (volume: 50.0 mL) in this order. The reaction mixture was stirred at 150 °C for a given time. The unreacted ethylene and TFE were purged from the reactor (caution: The reaction mixture must be handle in well-ventilated fume hood!!). The reaction mixture was quenched under air, and filtrated to remove insoluble residue. All volatiles were removed under reduced pressure, the crude product was further purified by Kugelrohr distillation, giving the title compound **2**. In the case of **1a**, the undesired **3a** was removed by silica gel column chromatography (elute: hexane: AcOEt = 95:5) after hydrolysis.

General procedure B for the substrate scope with the respect to aldehydes: A toluene solution (0.6 mL) of $Ni(cod)_2$ (1.4 mg, 0.005 mmol), IPr (1.9 mg, 0.005 mmol), and an aldehyde (**1**: 0.10 mmol) was exposed to ethylene (3.5 atm) and TFE (1.5 atm) into a pressure-tight NMR tube in this order. The reaction mixture was heated at 150 °C for 1 h. Then, the unreacted ethylene and TFE were purged from the reactor (caution: The reaction mixture must be handle in well-ventilated fume hood!!). The reaction mixture was quenched under air. After the addition of C_6D_6 and α,α,α-trifluorotoluene (5.0 μL) as the internal standard, the yield of the desired product **2** was estimated by ^{19}F NMR analysis.

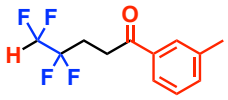


4,4,5,5-tetrafluoro-1-phenylpentan-1-one (2a): The general procedure A was followed with benzaldehyde (**1a**: 106.0 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. To remove **3a**, the filtrate was treated with a MeOH solution (3.0 mL) of KOH (3.0 mmol). Then, the ether extraction was concentrated in vacuo and the residue was purified by silica gel column chromatography (elute: hexane: AcOEt = 95:5) to give the title compound **2a** (186.5 mg, 80%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.48 (tt, J = 7.8 Hz, 19.0 Hz, 2H), 3.28 (t, J = 7.8 Hz, 2H), 5.79 (tm, J = 53.8 Hz, 1H), 7.49 (dd, J = 7.2 Hz, 7.4 Hz, 2H), 7.59 (t, J = 7.4 Hz, 1H), 7.99 (d, J = 7.2 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.6 (t, J = 22.1 Hz), 30.0 (t, J = 3.0 Hz), 110.5 (tt, J = 39.8 Hz, 249.1 Hz), 118.2 (t, J = 28.9 Hz), 128.3 (s), 129.0 (s), 133.7 (s), 136.5 (s), 197.3 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –119.7 (t, J = 19.0 Hz, 2F), –138.7 (d, J = 53.8 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{11}H_{10}F_4O$: 234.0668, (M^+) Found: 234.0669.

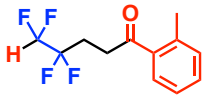


4,4,5,5-tetrafluoro-1-(*p*-tolyl)pentan-1-one (2b): The general procedure A was followed with *p*-

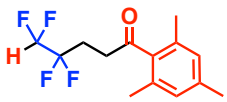
tolaldehyde (**1b**: 120.3 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by Kugelrohr distillation gave the title compound **2b** (213.3 mg, 86%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.42 (s, 3H), 2.46 (tt, J = 7.9 Hz, 18.7 Hz, 2H), 3.25 (t, J = 7.9 Hz, 2H), 5.78 (tm, J = 53.9 Hz, 1H), 7.28 (d, J = 8.9 Hz, 2H), 7.88 (d, J = 8.9 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 21.8 (s), 24.6 (t, J = 22.2 Hz), 29.7 (t, J = 3.1 Hz), 110.4 (tt, J = 40.7 Hz, 250.0 Hz), 118.1 (tt, J = 29.7 Hz, 244.8 Hz), 128.3 (s), 129.6 (s), 134.0 (s), 144.5 (s), 196.8 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.0 (t, J = 19.0 Hz, 2F), –137.8 (d, J = 53.9 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{12}H_{12}F_4O$: 248.0824, (M^+) Found: 248.0422.



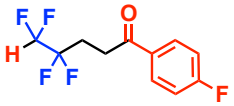
4,4,5,5-tetrafluoro-1-(*m*-tolyl)pentan-1-one (2c): The general procedure A was followed with *m*-tolaldehyde (**1c**: 119.5 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by Kugelrohr distillation gave the title compound **2c** (184.3 mg, 74%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.43 (s, 3H), 2.47 (tt, J = 7.7 Hz, 19.0 Hz, 2H), 3.27 (t, J = 7.7 Hz, 2H), 5.79 (tm, J = 53.5 Hz, 1H), 7.39 (m, 2H), 7.77 (d, J = 7.2 Hz, 1H), 7.79 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 21.5 (s), 24.5 (t, J = 22.2 Hz), 29.9 (t, J = 2.7 Hz), 110.4 (tt, J = 41.2 Hz, 249.5 Hz), 118.1 (tt, J = 29.7 Hz, 246.1 Hz), 125.4 (s), 128.7 (s), 128.7 (s), 134.4 (s), 136.5 (s), 138.7 (s), 197.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.8 (t, J = 19.0 Hz, 2F), –137.7 (d, J = 53.5 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{12}H_{12}F_4O$: 248.0824, (M^+) Found: 248.0823.



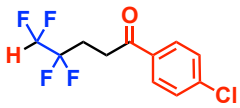
4,4,5,5-tetrafluoro-1-(*o*-tolyl)pentan-1-one (2d): The general procedure A was followed with *o*-tolaldehyde (**1d**: 120.1 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by Kugelrohr distillation gave the title compound **2d** (152.8 mg, 62%) as a colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.46 (tt, J = 7.6 Hz, 17.9 Hz, 2H), 2.51 (s, 3H), 3.20 (t, J = 7.6 Hz, 2H), 5.77 (tm, J = 53.7 Hz, 1H), 7.22–7.36 (m, 2H), 7.40 (dd, J = 7.7 Hz, 7.7 Hz, 1H), 7.69 (d, J = 7.7 Hz 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 21.5 (s), 24.6 (t, J = 22.3 Hz), 32.4 (t, J = 3.1 Hz), 110.4 (tt, J = 41.1 Hz, 249.9 Hz), 118.1 (tt, J = 29.1 Hz, 246.8 Hz), 126.0 (s), 128.7 (s), 131.9 (s), 132.3 (s), 137.1 (s), 138.7 (s), 200.7 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.7 (t, J = 17.9 Hz, 2F), –137.8 (d, J = 53.7 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{12}H_{12}F_4O$: 248.0824, (M^+) Found: 248.0823.



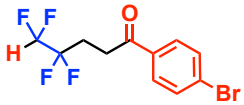
4,4,5,5-tetrafluoro-1-mesitylpentan-1-one (2e): The general procedure B was followed with 2,4,6-trimethylbenzaldehyde (**1e**: 14.8 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the yield of **2e** was 15%. **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –119.5 (t, J = 18.7 Hz, 2F), –138.1 (d, J = 53.4 Hz, 2F).



4,4,5,5-tetrafluoro-1-(4-fluorophenyl)pentan-1-one (2f): The general procedure A was followed with 4-fluorobenzaldehyde (**1g**: 124.3 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by Kugelrohr distillation gave the title compound **2f** (180.1 mg, 71%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.47 (tt, J = 7.9 Hz, 18.9 Hz, 2H), 3.25 (t, J = 7.9 Hz, 2H), 5.78 (tm, J = 53.8 Hz, 1H), 7.15 (d, J = 8.5 Hz, 2H), 8.01 (d, J = 8.5 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.5 (t, J = 22.5 Hz), 29.8 (t, J = 3.2 Hz), 110.4 (tt, J = 40.6 Hz, 250.0 Hz), 116.0 (d, J = 21.7 Hz), 118.0 (tt, J = 28.7 Hz, 246.1 Hz), 130.7 (d, J = 9.4 Hz), 132.9 (d, J = 3.0 Hz), 166.1 (d, J = 254.3 Hz), 195.6 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –107.1 (m, 1F), –118.7 (t, J = 18.9 Hz, 2F), –137.7 (d, J = 53.9 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{11}H_9F_5O$, 252.0574, (M^+) Found: 252.0574.

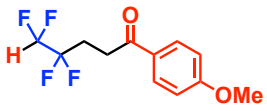


An attempt at preparation of 4,4,5,5-tetrafluoro-1-(4-chlorophenyl)pentan-1-one (2g): The general procedure B was followed with 4-chrolobenzladyde (**1g**: 14.1 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the target compound was not obtained, and the generation of Ni black was observed in the reaction mixture.

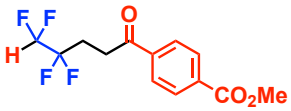


An attempt at preparation of 4,4,5,5-tetrafluoro-1-(4-bromophenyl)pentan-1-one (2h): The general procedure B was followed with 4-bromobenzladyde (**1h**: 18.5 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the target compound was not obtained, and the generation of Ni black was

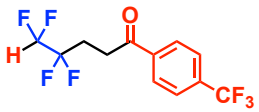
observed in the reaction mixture.



4,4,5,5-tetrafluoro-1-(4-methoxyphenyl)pentan-1-one (2i): The general procedure A was followed with *p*-anisaldehyde (**1i**: 136.6 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by Kugelrohr distillation gave the title compound **2i** (230.7 mg, 87%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.46 (m, J = 7.9 Hz, 18.7 Hz, 2H), 3.23 (t, J = 7.9 Hz, 2H), 3.88 (s, 3H), 5.78 (tm, J = 53.7 Hz, 1H), 6.96 (d, J = 8.9 Hz, 2H), 7.96 (d, J = 8.9 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.6 (t, J = 22.2 Hz), 29.4 (t, J = 2.6 Hz), 55.6 (s), 110.4 (tt, J = 41.1 Hz, 249.7 Hz), 114.0 (s), 118.1 (tt, J = 29.5 Hz, 245.9 Hz), 129.5 (s), 130.4 (s), 163.9 (s), 195.7 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.2 (t, J = 18.7 Hz, 2F), –137.8 (d, J = 53.7 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{12}H_{12}F_4O_2$: 264.0773, (M^+) Found: 264.0773.

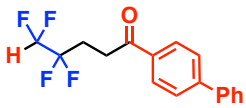


methyl 4-(4,4,5,5-tetrafluoropentanoyl)benzoate (2j): The general procedure A was followed with 4-formylbenzoate (**1j**: 163.7 mg, 1.0 mmol) in the presence of 10 mol% of $Ni(cod)_2$ and IPr, and the reaction mixture was stirred at 150 °C for 24 h. Purification by Kugelrohr distillation gave the title compound **2j** (227.3 mg, 78%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.50 (tt, J = 7.5 Hz, 18.1 Hz, 2H), 3.30 (t, J = 7.5 Hz, 2H), 3.96 (s, 3H), 5.79 (tt, J = 2.6 Hz, 54.0 Hz, 1H), 8.03 (d, J = 8.4 Hz, 2H), 8.14 (d, J = 8.4 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.4 (t, J = 22.4 Hz), 30.3 (t, J = 3.1 Hz), 52.6 (s), 110.4 (tt, J = 41.1 Hz, 248.6 Hz), 118.0 (tt, J = 29.8 Hz, 246.6 Hz), 128.1 (s), 130.1 (s), 134.5 (s), 139.6 (s), 166.2 (s), 196.7 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.5 (t, J = 18.1 Hz, 2F), –137.6 (d, J = 54.0 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{13}H_{12}F_4O_3$, 292.0723, (M^+) Found: 292.0723.

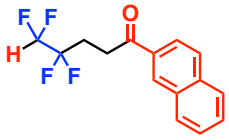


4,4,5,5-tetrafluoro-1-(4-(trifluoromethyl)phenyl)pentan-1-one (2k): The general procedure A was followed with 4-trifluoromethylbenzalhdehyde (**1k**: 174.2 mg, 1.0 mmol) in the presence of 10 mol%

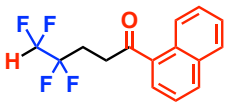
of $Ni(cod)_2$ and IPr, and the reaction mixture was stirred at 150 °C for 24 h. Purification by Kugelrohr distillation gave the title compound **2k** (71.5 mg, 24%) as a colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.50 (tt, J = 7.5 Hz, 19.0 Hz, 2H), 3.31 (t, J = 7.5 Hz, 2H), 5.78 (tt, J = 2.6 Hz, 53.9 Hz, 1H), 7.76 (d, J = 8.2 Hz, 2H), 8.10 (d, J = 8.2 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.4 (t, J = 22.3 Hz), 30.3 (t, J = 2.8 Hz), 110.4 (tt, J = 41.4 Hz, 249.5 Hz), 118.0 (tt, J = 29.0 Hz, 246.1 Hz), 123.7 (q, J = 272.6 Hz), 126.0 (q, J = 3.8 Hz), 128.5 (s), 135.0 (q, J = 32.8 Hz), 139.1 (s), 196.1 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –65.8 (s, 3F), –118.5 (t, J = 19.0 Hz, 2F), –137.7 (d, J = 53.9 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{12}H_9F_7O$, 302.0542, (M^+) Found: 302.0540.



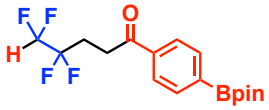
1-([1,1'-biphenyl]-4-yl)-4,4,5,5-tetrafluoropentan-1-one (2l): The general procedure B was followed with 4-phenylbenzaldehyde (**1l**: 18.1 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the yield of **2l** was 32%. **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –119.7 (t, J = 19.0 Hz, 2F), –138.1 (d, J = 53.8 Hz, 2F).



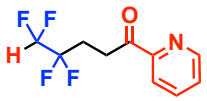
4,4,5,5-tetrafluoro-1-(naphthalen-1-yl)pentan-1-one (2m): The general procedure A was followed with 2-naphtaldehyde (**1m**: 156.2 mg, 1.0 mmol) in the presence of 10 mol% of $Ni(cod)_2$ and IPr, and the reaction mixture was stirred at 150 °C for 24 h. Purification by Kugelrohr distillation gave the title compound **2m** (152.7 mg, 54%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.57 (tt, J = 7.7 Hz, 18.5 Hz, 2H), 3.37 (t, J = 7.7 Hz, 2H), 5.70 (tt, J = 2.6 Hz, 53.8 Hz, 1H), 7.52 (m, 1H), 7.55 (m, 1H), 7.62 (m, 1H), 7.89 (d, J = 7.9 Hz, 1H), 7.93 (d, J = 7.2 Hz, 1H), 8.02 (d, J = 8.2 Hz, 1H), 8.64 (d, J = 8.6 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.9 (t, J = 22.3 Hz), 33.0 (t, J = 3.3 Hz), 110.4 (tt, J = 41.1 Hz, 251.2 Hz), 118.1 (tt, J = 28.2 Hz, 246.8 Hz), 124.5 (s), 125.8 (s), 126.7 (s), 128.0 (s), 128.3 (s), 128.6 (s), 130.3 (s), 133.4 (s), 134.2 (s), 135.1 (s), 201.0 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.6 (t, J = 18.5 Hz, 2F), –137.7 (d, J = 53.8 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{15}H_{12}F_4O$, 284.0824, (M^+) Found: 284.0824.



4,4,5,5-tetrafluoro-1-(naphthalen-2-yl)pentan-1-one (2n): The general procedure A was followed with 2-naphtaldehyde (**1n**: 156.2 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by Kugelrohr distillation gave the title compound **2n** (255.6 mg, 90%) as white solid. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.54 (tt, J = 7.9 Hz, 18.2 Hz, 2H), 3.43 (t, J = 7.9 Hz, 2H), 5.82 (tt, J = 2.5 Hz, 53.8 Hz, 1H), 7.60 (m, 2H), 7.89 (br, 1H), 7.92 (br, 1H), 7.99 (br, 1H), 8.05 (br, 1H), 8.51 (br, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.6 (t, J = 22.3 Hz), 29.9 (t, J = 3.0 Hz), 110.4 (tt, J = 42.5 Hz, 249.7 Hz), 118.1 (tt, J = 30.0 Hz, 244.7 Hz), 123.8 (s), 127.1 (s), 128.0 (s), 128.8 (s), 128.9 (s), 129.8 (s), 130.0 (s), 132.6 (s), 133.8 (s), 135.9 (s), 197.1 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.7 (t, J = 18.2 Hz, 2F), –137.7 (d, J = 53.8 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{15}H_{12}F_4O$, 284.0824, (M^+) Found: 284.0824.

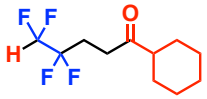


4,4,5,5-tetrafluoro-1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)pentan-1-one (2o): The general procedure A was followed with 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzaldehyde (**1o**: 232.1 mg, 1.0 mmol) in the presence of 10 mol% of $Ni(cod)_2$ and IPr, and the reaction mixture was stirred at 150 °C for 3 h. Purification by Kugelrohr distillation gave the title compound **2o** (266.4 mg, 74%) as a colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 1.35 (s, 12H), 2.47 (tt, J = 7.8 Hz, 18.3 Hz, 2H), 3.28 (t, J = 7.8 Hz, 2H), 5.78 (tm, J = 54.0 Hz, 1H), 7.91 (d, J = 15.7 Hz, 2H), 7.93 (d, J = 15.7 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 24.5 (t, J = 22.2 Hz), 25.0 (s), 30.0 (s), 77.4 (s), 84.4 (s), 110.4 (tt, J = 40.8 Hz, 250.5 Hz), 118.0 (tt, J = 17.2 Hz, 245.0 Hz), 127.1 (s), 135.2 (s), 138.3 (s), 197.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.8 (t, J = 18.3 Hz, 2F), –137.8 (d, J = 54.0 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{21}BF_4O_3$, 360.1520, (M^+) Found: 360.1521.

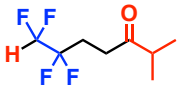


An attempt at preparation of 4,4,5,5-tetrafluoro-1-(pyridin-2-yl)pentan-1-one (2p): The general procedure B was followed with 2-pyridine-carboxaldehyde (**1p**: 10.7 mg, 0.10 mmol). ^{19}F NMR analysis indicated that the target compound was not obtained, and the generation of nickel black was

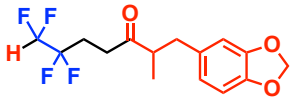
observed in the reaction mixture.



1-cyclohexyl-4,4,5,5-tetrafluoropentan-1-one (2q): The general procedure B was followed with cyclehexanecarboaldehyde (**1q**: 11.2 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the yield of **2q** was 57%. **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –119.8 (t, J = 18.5 Hz, 2F), –138.2 (d, J = 53.8 Hz, 2F). Attempt to isolate **2q** hampered due to its relatively-high volatility.

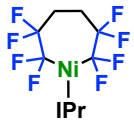


6,6,7,7-tetrafluoro-2-methylheptan-3-one (2r): The general procedure B was followed with isobytyraldehyde (**1r**: 7.2 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the yield of **2r** was 13%. **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –119.9 (t, J = 18.7 Hz, 2F), –138.2 (d, J = 53.7 Hz, 2F).



1-(benzo[d][1,3]dioxol-5-yl)-6,6,7,7-tetrafluoro-2-methylheptan-3-one (2s): The general procedure A was followed with 2-methyl-3-(3,4methylenedioxy- phenyl)-propanal (**1s**: 192.0 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by Kugelrohr distillation gave the title compound **2s** (151.5 mg, 47%) as a colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 1.10 (d, J = 3.7 Hz, 3H), 2.22 (m, 2H), 2.47 (m, 1H), 2.52 (m, 1H), 2.70 (m, 1H), 2.85 (m, 2H), 5.69 (tt, J = 2.6 Hz, 54.0 Hz, 1H), 5.91 (s, 2H), 6.57 (dd, J = 1.4 Hz, 7.9 Hz, 1H), 6.62 (d, J = 1.4 Hz, 1H), 6.71 (d, J = 7.9 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 16.5 (s), 24.0 (t, J = 22.8 Hz), 33.0 (t, J = 2.7 Hz), 39.1 (s), 48.6 (s), 101.0 (s), 108.4 (s), 109.3 (s), 110.3 (tt, J = 41.0 Hz, 248.6 Hz), 117.9 (tt, J = 29.7 Hz, 246.4 Hz), 121.9 (s), 133.2 (s), 146.3 (s), 147.9 (s), 211.2 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –118.9 (t, J = 18.3 Hz, 2F), –137.8 (d, J = 54.0 Hz, 2F). **HRMS (EI)**: *m/z* Calcd for $C_{15}H_{16}F_4O_3$, 320.1036, (M^+) Found: 320.1037.

A stoichiometric reaction of $(CF_2CF_2CH_2CH_2)Ni(PPh_3)_2$ (I) with 1a: A C_6D solution (0.5 mL) of $(CF_2CF_2CH_2CH_2)Ni(PPh_3)_2$ (**I**: 7.1 mg, 0.01 mmol) and **1a** (10.6 mg, 0.10 mmol) was heated at 40 °C for 3 h in a sealed NMR tube to give **2a** in 94% yield with a concomitant formation of (η^2-PhCHO)$Ni(PPh_3)_2$.



Preparation of ($CF_2CF_2CH_2CH_2CF_2CF_2$)Ni(IPr) (II): A toluene (6.0 mL) solution of $Ni(cod)_2$ (82.9 mg, 0.30 mmol) and IPr (117.7 mg, 0.30 mmol) was transferred into an autoclave reactor. Then, ethylene (3.5 atm) and TFE (1.5 atm) were charged into the reactor in this order. The reaction mixture was stirred at room temperature for 24 h. All volatiles were removed under reduced pressure, and residue was washed with hexane to afford **II** (142 mg, 70%) as purple solid. A single crystal for X-ray diffraction analysis was prepared by recrystallization from toluene/hexane at room temperature. **^{1}H NMR** (400 MHz, C_6D_6, rt, δ/ppm): 1.01 (d, J = 6.9 Hz, 12H, -CH_3), 1.58 (d, J = 6.8 Hz, 12H, -CH_3), 1.65 (br, 4H, -CH_2-), 2.78 (qq, J = 6.8 Hz, 6.9 Hz, 4H, -CH(CH_3)$_2$), 6.46 (s, 2H), 7.18 (br, 4H), 7.29 (br, 4H). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_6, rt, δ/ppm): 23.4 (s, -CH$_3$), 25.8 (s, -CH$_3$), 27.4 (tt, J = 5.2 Hz, 27.5 Hz, -CH$_2$-), 29.1 (s, -CH(CH_3)$_2$), 124.5 (s, aromatic-C), 124.6 (s, aromatic-C), 130.8 (s, aromatic-C), 134.8 (s, aromatic-C), 146.2 (s, -HC=CH-). Resonances attributable to the CF_2CF_2 moiety could not be detected due to multiple ^{13}C–^{19}F couplings. **^{19}F NMR** (376 MHz, C_6D_6, rt, δ/ppm): –110.7 (s, 4F, CF_2), –114.7 (s, 4F, CF_2). **Anal. Calcd** for $C_{33}H_{40}F_8N_2Ni$: C, 58.69; H, 5.97; N, 4.15. Found: C, 58.40; H, 6.04; N, 4.17. **X-ray data** for **II**. M = 675.38, platelet, purple, monoclinic, $P2_1$ (#4), a = 10.3010(5) Å, b = 19.2677(8) Å, c = 16.8297(7) Å, = 100.001(2), V = 3289.6(3) Å^3, Z = 4, Dcalcd = 1.364 g/cm^3, T = –150 °C, R_1 (wR_2) = 0.0552 (0.0866), Flack parameter 0.015(9).

A stoichiometric reaction of ($CF_2CF_2CH_2CH_2CF_2CF_2$)Ni(IPr) (II) with 1a: A toluene-d_8 solution (0.5 mL) of **II** (6.8 mg, 0.01 mmol) and **1a** (10.6 mg, 0.10 mmol) was heated at 150 °C for 1 h into a sealed NMR tube. NMR analysis revealed that neither **2a** nor **3a** was formed, whereas **II** was completely consumed. Some of the ^{19}F NMR resonances were found to be identical to those observed in the thermolysis products of **II** at 150 °C in the absence of **1a**. The thermolysis products were unidentified. When **II** was treated with **1a** in C_6D_6 at 40 °C for 3 h, **II** was completely consumed to give a complicated mixture, but **2a** was not contained in the mixture.

2.8 References and Notes

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Chapter 3

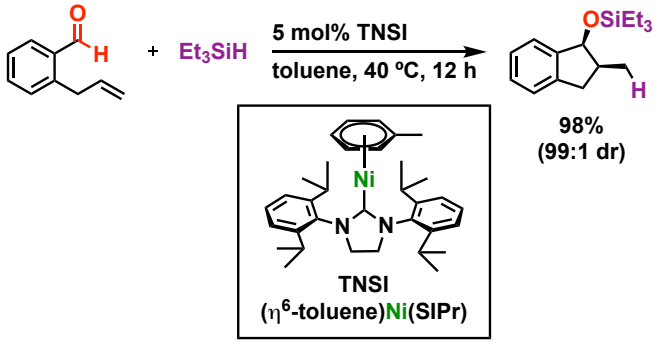
Ni(0)-Catalyzed Three-Component Coupling Reaction of Tetrafluoroethylene and Aldehydes with Silanes via Oxa-Nickelacycle Key Intermediates

3.1 Introduction

The oxidative cyclization with Ni(0) naturally proceeds with a variety of combinations of two π-components to produce the corresponding nickelacycle.[1] While a catalytic reaction via such hetero-nickelacycles generated from TFE and a carbonyl compound has not been studied, we envisioned that oxa-nickelacycles generated from TFE and aldehydes could potentially serve as key intermediates in a Ni(0)-catalyzed three-component coupling reaction. Ni(0)-catalyzed three-component coupling reactions have been developed with various substrate combinations so far.[2] However, the number of combination of alkenes and aldehydes remain relatively limited. This is due to a crucial difference in the coordination ability of alkenes and aldehydes to Ni(0), where the coordination ability of aldehydes to Ni(0) is stronger than that of alkenes. This reveals that the simultaneous coordination of alkenes and aldehydes to Ni(0) is problematical, results in the oxidative cyclization of alkenes and aldehyde could not proceed. Thus, Ni(0)-catalyzed three-component coupling reactions between alkenes and aldehydes have only been reported in the case of intermolecular reactions of highly reactive strained alkenes such as methylenecyclopronane and norbornene (Scheme 3.1)[3] or an intramolecular reaction of *o*-allylbenzaldehyde derivatives (Scheme 3.2).[4, 5]

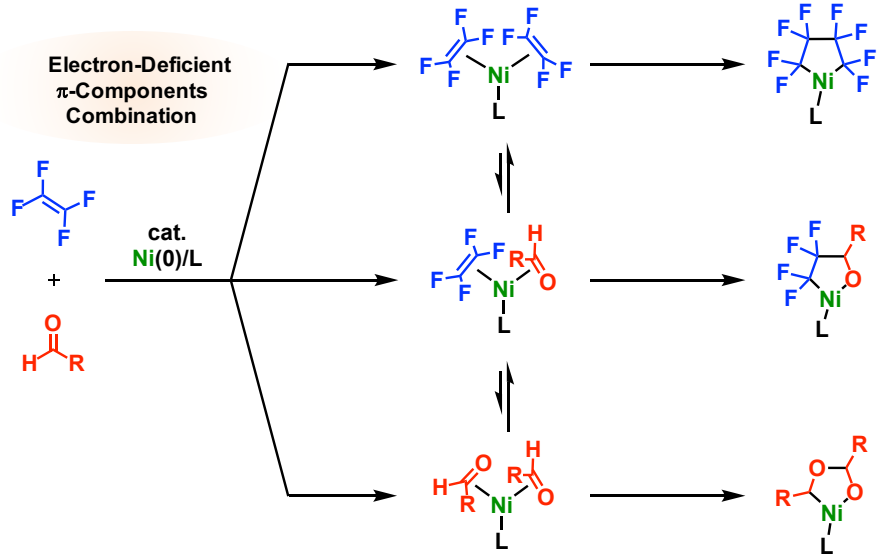
Scheme 3.1. Ni(0)-Catalyzed Three-Component Coupling Reactions of Strained Alkenes and Aldehydes.

Scheme 3.2. Ni(0)-Catalyzed Intramolecular Three-Component Coupling Reaction.



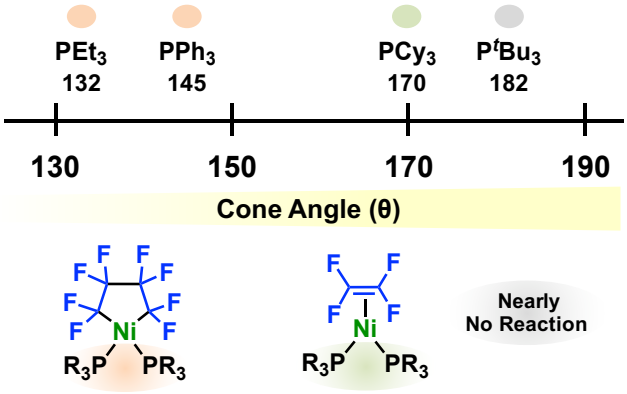
The Ni(0)-catalyzed three-component coupling reaction with a combination of TFE and aldehydes is much more challenging since the oxidative cyclization of TFE and an aldehyde, i.e. a combinations of two electron-deficient π-components, is kinetically unfavorable (Figure 3.1). Considering η^2:η^2 nickel complexes in the catalytic reaction, (η^2-RCHO)$_2$Ni(0)L, (η^2-TFE)(η^2-RCHO)Ni(0)L, and (η^2-TFE) $_2$Ni(0)L are potentially generated in situ. In addition, the coordination ability of TFE should be superior to that of aldehydes due to the back-donation from Ni(0) to TFE. This reveals that the formation of (η^2-TFE)$_2$Ni(0)L is more favorable. Therefore, we estimated that the selective oxidative cyclization of TFE and aldehydes could proceed to generate the oxa-nickelacycles when the simultaneous coordination and the oxidative cyclization of two molecules of TFE are suppressed.

Figure 3.1. Selective Oxidative Cyclization between TFE and Aldehydes.

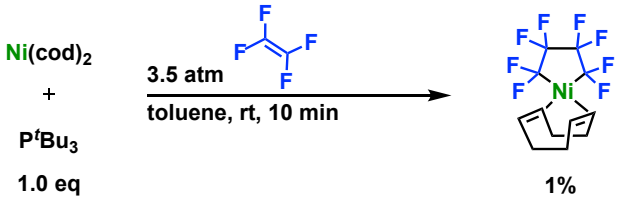


The simultaneous coordination and the oxidative cyclization of two molecules of TFE with Ni(0) could be controlled by the steric hindrance of monodentate phosphine ligands (Figure 3.2).[6] The use of PEt_3 and PPh_3, whose cone angles are relatively small, produces $(CF_2CF_2CF_2CF_2)Ni(PR_3)_2$ (R = Et or Ph), which is generated from two molecules of TFE. On the other hand, employing a relatively bulky ligand such as PCy_3 did not furnish the nickelacycle but (η^2-TFE)$Ni(PCy_3)_2$. In addition, when the reaction of $Ni(cod)_2$ and a bulky ligand such as P^tBu_3 with TFE was conducted, the reaction scarcely proceeded although mere trace amounts of the nickelacycle coordinated by cod was generated (Scheme 3.3). Thus, we estimated that the use of a bulky ligand should be important for the Ni(0)-catalyzed three-component coupling reaction of TFE and aldehydes with silanes.

Figure 3.2. Effects of Steric Bulkiness of Ligands.



Scheme 3.3. Reaction of $Ni(cod)_2$, P^tBu_3, and TFE.

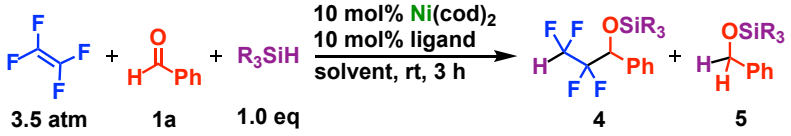


3.2 Optimization of the Reaction Conditions

Based on the hypothesis, the optimization of the reaction conditions for the Ni(0)-catalyzed three-component coupling reaction of TFE, aldehydes, and silanes was performed (Table 3.1). When a toluene solution of **1a** and Et_3SiH was exposed to TFE (3.5 atm) in the presence of $Ni(cod)_2$ (10 mol%) and P^tBu_3 (10 mol%) as a bulky ligand, the desired three-component coupling product, (2,2,3,3-tetrafluoro-1-phenylpropoxy)triethylsilane (**4a**), was generated in 72% yield (entry 1). In this reaction, the 1,2-addition of **1a** toward Et_3SiH furnished an undesired benzoxytriethylsilane (**5a**) in 3% yield. Employing PPh_3 (20 mol%) afforded neither **4a** nor **5a**

due to the undesired oxidative cyclization of two molecules of TFE (entry 2). The use of either PCy_3 (20 mol%) or IPr (10 mol%) furnished **4a** in 2% and 15% yield, respectively. However, **5a** was mainly generated since the 1,2-addition rapidly proceeded before the exposure of TFE gas (entries 3 and 4). Control experiments in the absence of either P^tBu_3 or $Ni(cod)_2$ showed that both are necessary for the catalytic reaction (entries 5 and 6). Subsequently, the reaction was further examined with a variety of silanes in the presence of $Ni(cod)_2$ and P^tBu_3. Employing both Et_3SiH and Ph_3SiH in C_6D_6 generated the corresponding target compounds in 90% and 89% yield, respectively, whereby the use of $(EtO)_3SiH$ yielded a trace amount of the desired product (entries 7–9). Indeed, the effect of the solvents was also examined. The yield with hexane was comparable to that with C_6D_6, while the yield with THF was less for the catalytic reaction (entries 10 and 11). This catalytic reaction with of $Ni(cod)_2$ and P^tBu_3 in hexane was completed in 1 h to produce **4a** in 88% yield. In this case, the homo-Tishchenko reaction product **2a** was also generated as a by-product in 4% yield (entry 12).[7] Therefore, the optimal reaction conditions were determined as follows: 10 mol% $Ni(cod)_2$ and P^tBu_3 in hexane at room temperature for 1 h.

Table 3.1. Optimization of the Reaction Conditions of the Ni(0)-Catalyzed Three-Component Coupling Reaction of TFE, 1a, and Silanes.



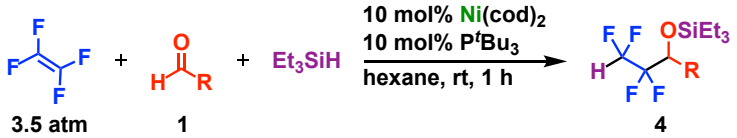
Entry	Ligand	R_3SiH	Solvent	Yield (%) 4	5
1	P^tBu_3	Et_3SiH	toluene	72	3
2[a]	PPh_3	Et_3SiH	toluene	0	0
3[a]	PCy_3	Et_3SiH	toluene	2	75
4	IPr	Et_3SiH	toluene	15	73
5	none	Et_3SiH	toluene	0	0
6[b]	P^tBu_3	Et_3SiH	toluene	0	0
7	P^tBu_3	Et_3SiH	C_6D_6	90	4
8	P^tBu_3	Ph_3SiH	C_6D_6	89	10
9	P^tBu_3	$(EtO)_3SiH$	C_6D_6	2	21
10	P^tBu_3	Et_3SiH	THF	48	4
11	P^tBu_3	Et_3SiH	hexane	88	2
12[c]	P^tBu_3	Et_3SiH	hexane	88	>1

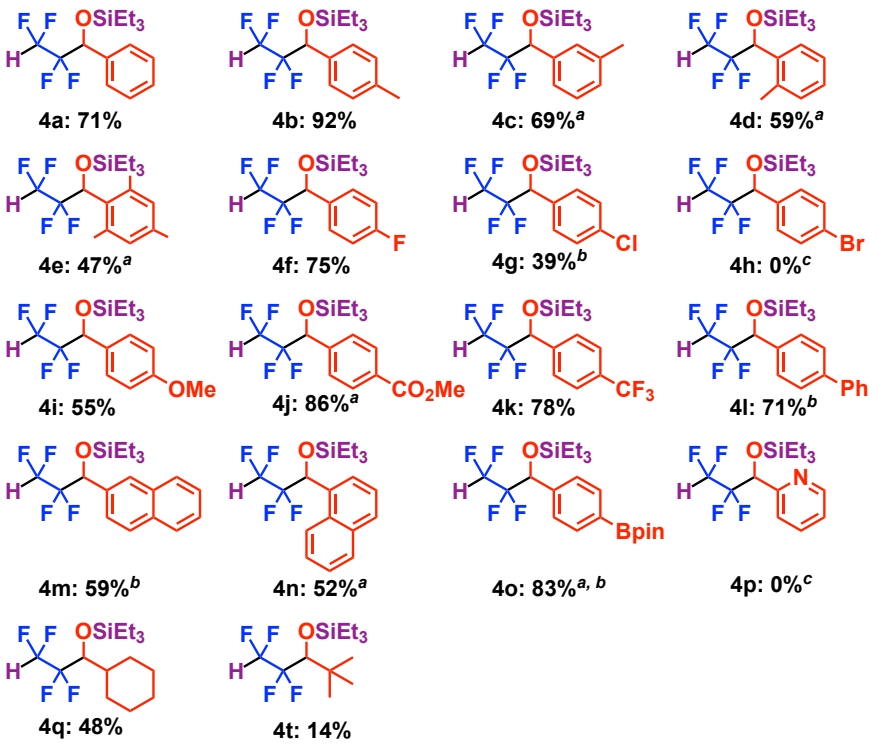
[a] Employment of 20 mol% of phosphine ligands. [b] Run without $Ni(cod)_2$. [c] Run for 1 h.

3.3 Substrate Scope

The scope of the Ni(0)-catalyzed three-component coupling reaction with respect to aldehydes was investigated under the optimal reaction conditions (Table 3.2). Some of the reactions had to be performed in a mixture of hexane/benzene due to the low solubility of the aldehydes. The Ni(0)/P^{t}Bu$_3$ system catalyzed the reaction of TFE, **1a**, and Et_3SiH to afford **4a** in 71% isolated yield. *p*-Tolualdehyde (**1b**) was an excellent substrate for the catalytic reaction, furnishing **4b** in 92% yield. The reactions of *m*-tolualdehyde (**1c**), *o*-tolualdehyde (**1d**), and mesitylaldehyde (**1e**) produced the corresponding products (**4c**–**e**) in moderate yield, although longer reaction time was required to complete the catalytic reaction. Employing *p*-fluorobenzaldehyde (**1f**) afforded the target product (**4f**) in 75% yield while the use of *p*-chlorobenzaldehyde (**1g**) generated a lower yield (39%) of the target product (**4g**), and unreacted starting material was observed. The low conversion is probably due to the deactivation of the nickel catalyst by the undesired oxidative addition of Ni(0) to a C–Cl bond. Thus, the reaction of *p*-bromobenzaldehyde (**1h**) could not be used as a substrate in the catalytic reaction. *p*-Anisaldehyde (**1i**) was tolerated to afford **4i** in 55% yield. When electron-deficient aromatic aldehydes including metyl 4-formylbenzoate (**1j**), *p*-trifluoromethylbenzaldehyde (**1k**), and 4-biphenylaldehyde (**1l**) were used for the catalytic reaction, the corresponding products (**4j**–**l**) was generated in good yield. Both 1-naphthaldehyde (**1m**) and 2-naphthaldehyde (**1n**) furnished **4m** and **4n** in 59% and 52% yield, respectively. The *p*-boronate substituted silyl ether (**4o**), which could be further used as a coupling reagent in a cross-coupling reaction, was also prepared in 83% yield via the reaction with the *p*-boronate substituted aldehyde (**1o**). 2-pyridyl aldehyde (**1p**) did not afford the target product (**4p**), which was confirmed by ^{19}F NMR analysis of the crude reaction mixture. This might be due to the deactivation of the nickel catalyst on account of the undesired coordination of the nitrogen atom on **1p** to Ni(0) species. The use of cyclohexanecarboxaldehyde (**1q**) generated the target product (**4p**) in 48% yield while the use of pivalaldehyde (**1t**) afforded the low yield (14%) of **4t** since the undesired 1,2-addition of **1t** with Et_3SiH and homo-Tishchenko reaction of **1t** proceeded as side reactions.

Table 3.2. Substrate Scope of the Ni(0)-Catalyzed Three-Component Coupling Reaction of TFE, Aldehydes (1), and Et_3SiH.





[a] Run for 3 h. [b] Solvent: hexane:benzene = 2:1 (v/v).
[c] Yield was estimated by ^{19}F NMR analysis of the crude reaction mixture.

3.4 Stoichiometric Reactions

Stoichiometric experiments were conducted in order to gain deeper insight into the reaction mechanism. A hexane solution of $Ni(cod)_2$, P^tBu_3, and **1a** was exposed to TFE, and the reaction mixture was stirred at room temperature for 3 h. Then, recrystallization from THF and pentane was conducted to produce an oxa-nickelacycle dimer complex coordinated by THF (***syn*-III**) in 90% isolated yield (Scheme 3.4). The molecular structure of ***syn*-III** was confirmed by single-crystal X-ray diffraction analysis, which revealed a cyclic framework composed of TFE, **1a**, and nickel (Figure 3.2a). The sum of the bond angles around the nickel center of ***syn*-III** is ~360°, indicating a distorted square-planar geometry in the solid state. When this reaction mixture was monitored by ^{19}F and ^{31}P NMR analysis in toluene-d_8, broadened resonances were observed even at low temperature, which revealed that dimerization equilibrium of the oxa-nickelacycle units

accompanied by a P^tBu_3 coordination/dissociation process. When this reaction was conducted in the absence of P^tBu_3 in a THF solution, ***syn*-III** was not generated, which suggested that P^tBu_3 was essential for the oxidative cyclization. Subsequently, the reaction of ***syn*-III** with P^tBu_3 and $BF_3{\cdot}Et_2O$ produced the oxa-nickelacycle monomer complex (**IV**) in 99% isolated yield. The single-crystal X-ray diffraction analysis showed a distorted T-shaped configuration (Figure 3.2b). The dissociation of P^tBu_3 from **IV** does not occur in C_6D_6 as the coupling between the α-CF_2 fluorine atom and the P^tBu_3 phosphorus atom is evident from both the ^{19}F and the ^{31}P NMR spectra. These results revealed again that the oxa-nickelacycle dimer dissociates into the corresponding monomer in the presence of the P^tBu_3. In addition, the reaction of ***syn*-III** with PCy_3 produced the PCy_3-ligated oxa-nickelacycle dimer complex (***syn*-V**) in 98% yield. Its molecular structure was a distorted square-planar geometry in the solid state, which was confirmed by single-crystal X-ray diffraction analysis (Figure 3.2c).

Scheme 3.4. Preparation of Oxa-Nickelacycles.

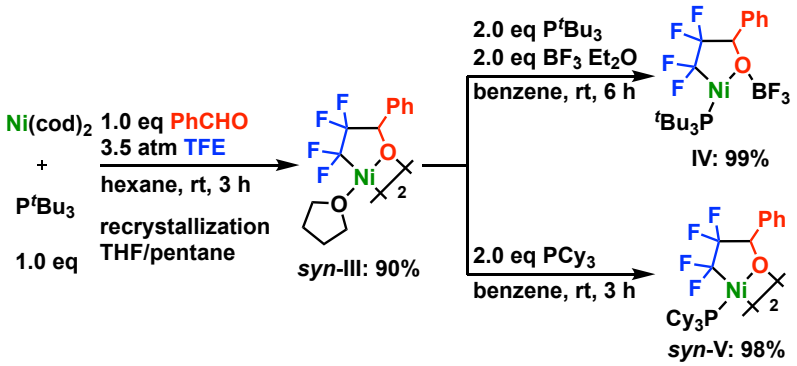
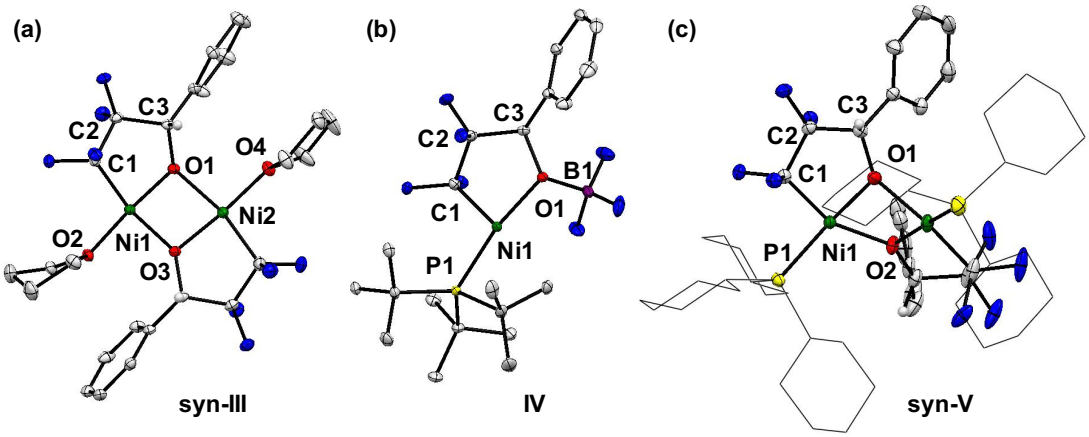
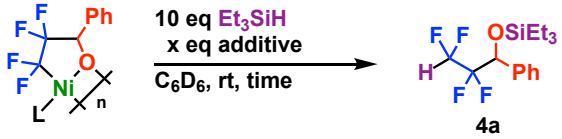


Figure 3.2. ORTEP representations of (a) *syn*-III, (b) IV, and (c) *syn*-V with thermal ellipsoids at the 30% probability; (except for the organic substituents of the phosphine ligands in *syn*-V); selected hydrogen atoms have been omitted for clarity.



When the reaction of ***syn*-III** with Et_3SiH was conducted in the absence of P^tBu_3, the target compound **4a** was not generated (Table 3.3, entry 1). On the other hand, **4a** was formed in 67% yield when P^tBu_3 was used for the reaction as an additional ligand (entry 2). Based on these results, the catalytic reaction most likely proceeds via an oxa-nickelacycle monomer generated from TFE and aldehydes, while both the oxa-nickelacycle monomer and dimer could be key intermediates in the catalytic reaction. In addition, treatment of **IV** with Et_3SiH at room temperature for 1 h furnished **4a** in 4% yield, although unreacted **IV** was detected by ^{19}F NMR analysis (entry 3). When the reaction time was extended to 24 h, the yield of **4a** was slightly improved to 16% yield (entry 4). The low reactivity of **IV** toward Et_3SiH was due to the O atom coordination to BF_3. Therefore, 1,4-diazabicyclo[2.2.2]octane **(**DABCO) was used as an additive to dissociate BF_3 from the O atom of **IV**, which resulted in the generation of **4a** in 21% yield (entry 5).[8] In this reaction, the conversion of **IV** reached in fact 100%, whereby the relatively low yield of **4a** should be due to decomposition of **IV**. These results revealed that the Si atom of Et_3SiH approaches the O atom of the oxa-nickelacycle monomer, which facilitates the transmetallation with Et_3SiH. It should be noted that the reaction of **IV**, DABCO, and $(EtO)_3SiH$, which is an ineffective silane in the catalytic reaction, did not afford the target compound. This result suggests that the transmetallation of the oxa-nickelacycle with such silanes should be a difficult step. Since the reaction of ***syn*-V** with Et_3SiH gave no target compound, we concluded the steric hindrance of the phosphine ligand may be important for not only the selective oxidative cyclization but also the dissociation of the dimer complex into the monomer (entry 6).[9]

Table 3.3. Stoichiometric Reactions with the Oxa-Nickelacycles.

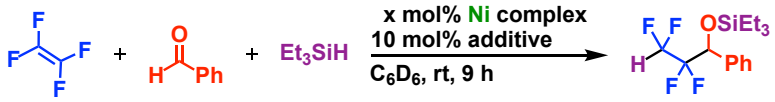


4a

Entry	Ni complex	Additive (x)	Time (h)	Yield (%)
1	*syn*-III	none	9	0
2	*syn*-III	P^tBu_3 (2.0)	9	67
3	IV	none	1	4
4	IV	none	24	16
5	IV	DABCO (1.0)	2	21
6	*syn*-V	none	9	0

In addition, the catalytic reactions were conducted in the presence of the isolated oxa-nickelacycles (Table 3.4). While the use of only ***syn*-III** as the catalyst furnished no target product, the reaction with ***syn*-III** and P^{t}Bu$_3$ afforded **4a** in 50% yield (entries 1 and 2). The reaction with **IV** generated **4a** in 65% yield although the reaction proceeded even in the presence of DABCO as an additive to furnish **4a** in 49% yield (entries 3 and 4). On the other hand, employing ***syn*-V** was ineffective for the catalytic reaction. These results are consistent with the conclusions drawn from the stoichiometric reactions.

Table 3.4. Catalytic Reactions with the Oxa-Nickelacycles.



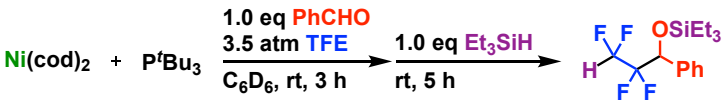
3.5 atm 1a 1.1 eq 4a

Entry	Ni complex (x)	Additive	Yield (%)[a]
1	*syn*-III (5)	none	0
2	*syn*-III (5)	P^{t}Bu$_3$	50
3	IV (10)	none	65
4	IV (10)	DABCO	49
5	*syn*-V (5)	none	0

[a] Yield was calculated based on Et_3SiH

We also confirmed that the target product could be obtained from a stoichiometric reaction without the need for isolating the oxa-nickelacycle complex (Scheme 3.5). A mixture of Ni(cod)$_2$, P^{t}Bu$_3$, and **1a** was exposed to TFE for 3 h. After purging the TFE, the addition of Et_3SiH afforded **4a** in 66% yield.

Scheme 3.5. A Stoichiometric Reaction without Isolating.



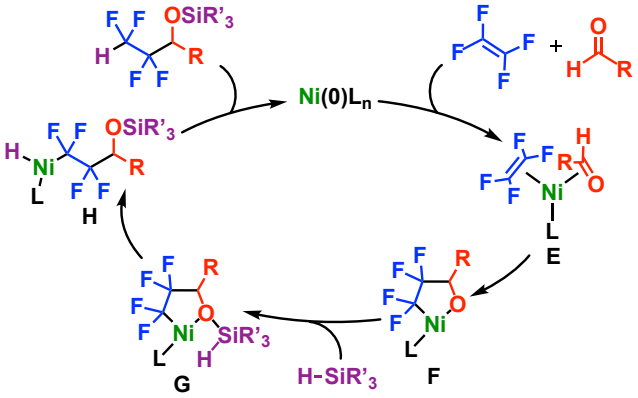
1.0 eq 4a: 66%

3.5 A Plausible Reaction Mechanism

Based on these results and those of previous studies on the reaction mechanism of Ni(0)-catalyzed three-component reactions,[10] a plausible reaction mechanism was shown in Scheme 3.6. A simultaneous coordination of TFE and aldehydes, which is combinations of two different

electron-deficient π-components, to Ni(0) affords η^2:η^2 nickel complex (**E**). Then, an oxidative cyclization of TFE and aldehydes with Ni(0) produces an oxa-nickelacycle (**F**) as key intermediates. The Si atom of the silane approaches the O atom of **F** to form oxa-nickelacycle (**G**). Finally, a transmetallation from **G** gives the nickel hydride (**H**), followed by a reductive elimination of Ni(II) from **H** to generate the desired product under concomitant regeneration of the Ni(0) species.

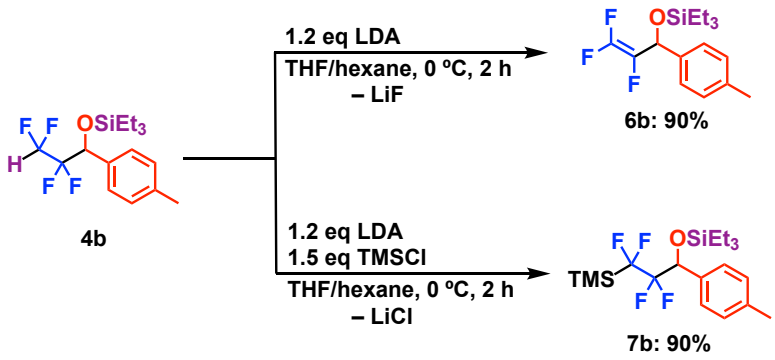
Scheme 3.6. A Plausible Reaction Mechanism.



3.6 Application

The reactivity and utility of the obtained reaction product **4b** are exemplified as shown in Scheme 3.7.[11] The addition of the Lewis base, lithium diisopropyl amide (LDA), deprotonated **4b** to afford the trifluoro allylic alcohol derivative (**6b**) in 90% isolated yield under concomitant generation of LiF. Such a trifluoro allylic alcohol derivative is a desirable co-monomer to tune the solubility of fluorine-containing polymers such as PTFE and ETFE on account of the hydroxyl group obtained from desilylation and the substituents on the aromatic ring. Furthermore, the transient fluoroalkyl lithium species formed upon deprotonation of **4b** by LDA can react with trimethylsilyl chloride (TMSCl) to furnish an organic silicon compound (**7b)** in 90% isolated yield.[12] Although tetrafluoroethylene-bridging alcohols are expected to be physiologically active, studies on the subject remain scarce due to a lack of efficient synthetic methods.[13] Therefore, the organic silicon compound might be used as a coupling reagent for the facile preparation of tetrafluoroethylene-bridging alcohols. These applications demonstrate the synthesis utility of the present catalytic reaction.

Scheme 3.7. Utility and Application of Fluorine Containing Silyl Ether 4b.



3.7 Conclusion

In Chapter 3, a Ni(0)-catalyzed three-component coupling reaction of TFE and aldehydes with silanes to afford fluorine-containing silyl ethers was demonstrated. The detailed mechanistic studies revealed that the oxidative cyclization of TFE and aldehydes with Ni(0) as a key C-C bond formation step in the catalytic reaction. The key to the successful selective oxidative cyclization between two different electron-deficient π-components, is the suppression of the oxidative cyclization of two molecules of TFE by a bulky phosphine ligand. In addition, the obtained products can be deprotonated by a Lewis base and transformed into trifluoro allylic alcohol derivatives or organic silicon compounds, which could be used as a co-monomer for the preparation of fluorine-containing polymers and a coupling reagent for the synthesis of physiologically active compounds.

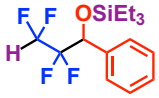
3.8 Experimental Section

General procedure for the optimization of the reaction conditions: The reactions were conducted with a pressure-tight NMR tube (Wilmad-LabGlass, 524-PV-7). A solution (0.6 mL) of $Ni(cod)_2$ (2.8 mg, 0.010 mmol), a given ligand, **1a** (0.10 mmol), and a given silane (0.10 mmol) was exposed to TFE (3.5 atm, >0.30 mmol). The reaction mixture was remained at room temperature for a given time. The yield of **4a** and **5a** were determined by gas chromatography using dodecane as the internal standard. When the studies on a variety of silanes, except for Et_3SiH, were conducted, the yield of the corresponding target compounds and by-products were determined by NMR using α,α,α-trifluorotoluene as the internal standard.

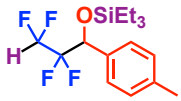
General procedure A for the substrate scope with the respect to aldehydes: A hexane solution (6.0 mL) of $Ni(cod)_2$ (27.5 mg, 0.10 mmol), P^tBu_3 (20.2 mg, 0.10 mmol), a given aldehyde (**1**: 1.0 mmol),

and Et_3SiH (116.3 mg, 0.10 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). When the reactions were conducted with insoluble aldehydes for hexane, the mixed solvent (hexane/benzene = 2:1 (v/v)) was used for the catalytic reaction. Then, TFE (3.5 atm) was charged into the autoclave reactor. The reaction mixture was stirred at room temperature for a given time. The unreacted TFE was purged from the autoclave reactor. (caution: The reaction mixture must be handle in a well-ventilated fume hood.) The reaction mixture was quenched under air and filtrated to remove insoluble residue. After all volatiles were removed under reduced pressure, the crude product was purified by silica gel column chromatography (elute: hexane:AcOEt = 99:1 to 9:1), giving the title compound **4**.

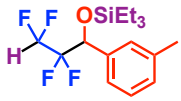
General Procedure B for the substrate scope with the respect to aldehydes: A hexane solution (0.6 mL) of $Ni(cod)_2$ (2.8 mg, 0.010 mmol), P^tBu_3 (2.0 mg, 0.010 mmol), aldehyde (**1**: 0.10 mmol), Et_3SiH (0.10 mmol) was transferred into a pressure-tight NMR tube. Then, TFE (3.5 atm, >0.30 mmol) was charged into the reaction tube. The reaction tube was remained at room temperature for 1 h. The unreacted TFE was purged from the reactor (caution: The reaction mixture must be handle in well-ventilated fume hood!!). The reaction mixture was quenched under air, and C_6D_6 and α,α,α-trifluorotoluene as the internal standard were added to estimate the yield of the desired product **4** by ^{19}F NMR analysis.



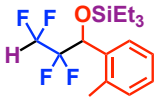
4,4,5,5-tetrafluoro-1-phenylpentan-1-one (4a): The general procedure A was followed with **1a** (106.0 mg, 1.0 mmol), and the reaction mixture was stirred at 150 °C for 1 h. Purification by silica gel column chromatography gave **4a** (229.5 mg, 71%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.55 (q, J = 7.9 Hz, 6H), 0.88 (t, J = 7.9 Hz, 9H), 4.99 (ddd, J = 16.8 Hz, 6.4 Hz, 1.6 Hz, 1H), 5.99 (dddd, J = 53.8 Hz, 52.8 Hz, 9.0 Hz, 2.3 Hz, 1H), 7.31–7.49 (5H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.5 (s), 6.4 (s), 73.1 (dd, J = 29.9 Hz, 23.3 Hz), 109.5 (dddd, J = 252.2 Hz, 247.9 Hz, 28.1 Hz, 3.5 Hz), 112.3 (s), 114.8 (dddd, J = 255.1 Hz, 252.8 Hz, 22.0 Hz, 1.6 Hz), 128.2 (s), 129.1 (s), 135.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.4 (m, J = 266.3 Hz, 12.3 Hz, 9.0 Hz, 6.8 Hz, 6.4 Hz, 1F), –133.3 (ddd, J = 266.3 Hz, 16.8 Hz, 12.1 Hz, 1F), –139.7 (ddd, J = 299.1 Hz, 52.8 Hz, 12.3 Hz, 1F), –144.2 (m, J = 299.1 Hz, 53.8 Hz, 12.1 Hz, 6.8 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{15}H_{22}F_4OSi$ + H: 323.1415, Found: 323.1454.



(2,2,3,3-tetrafluoro-1-(*p*-tolyl)propoxy)triethylsilane (4b): The general procedure A was followed with **1b** (120.2 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4b** (309.2 mg, 92%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.54 (q, J = 7.9 Hz, 6H), 0.88 (t, J = 7.9 Hz, 9H), 2.36 (s, 3H), 4.94 (ddd, J = 16.8 Hz, 6.6 Hz, 1.8 Hz, 1H), 5.97 (dddd, J = 54.2 Hz, 53.0 Hz, 8.8 Hz, 2.4 Hz, 1H), 7.18 (d, J = 7.8 Hz, 2H), 7.30 (d, J = 7.8 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.7 (s), 6.6 (s), 21.4 (s), 73.1 (dd, J = 30.1 Hz, 23.2 Hz), 109.6 (dddd, J = 251.2 Hz, 247.7 Hz, 28.3 Hz, 3.6 Hz), 115.0 (dddd, J = 254.3 Hz, 252.4 Hz, 22.2 Hz, 2.3 Hz), 128.2 (s), 129.0 (s), 132.4 (s), 139.1(s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.9 (m, J = 267.1 Hz, 12.7 Hz, 8.8 Hz, 6.9 Hz, 6.6 Hz, 1F), –133.7 (m, J = 267.1 Hz, 16.8 Hz, 13.1 Hz, 1F), –140.0 (m, J = 299.2 Hz, 53.0 Hz, 12.7 Hz, 1F), –144.4 (m, J = 299.2 Hz, 54.2 Hz, 13.1 Hz, 6.9 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{16}H_{24}F_4OSi$: 336.1533, Found: 336.1538.

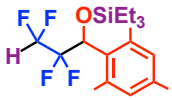


(2,2,3,3-tetrafluoro-1-(*m*-tolyl)propoxy)triethylsilane (4c): The general procedure A was followed with **1c** (120.2 mg, 1.0 mmol), and the reaction mixture was stirred for 3 h. Purification by silica gel column chromatography gave **4c** (233.1 mg, 69%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.55 (q, J = 7.9 Hz, 6H), 0.90 (t, J = 7.9 Hz, 9H), 2.39 (s, 3H), 4.95 (ddd, J = 17.0 Hz, 6.5 Hz, 1.9 Hz, 1H), 5.99 (dddd, J = 53.0 Hz, 52.8 Hz, 8.9 Hz, 2.7 Hz, 1H), 7.17–7.30 (4H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.7 (s), 6.6 (s), 21.5 (s), 73.2 (dd, J = 30.0 Hz, 23.3 Hz), 109.6 (dddd, J = 249.8 Hz, 248.5 Hz, 28.1 Hz, 3.9 Hz), 115.0 (dddd, J = 254.5 Hz, 252.9 Hz, 22.7 Hz, 1.7 Hz), 125.4 (s), 128.2 (s), 128.9 (s), 130.0 (s), 135.4 (s), 138.0(s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.8 (m, J = 265.5 Hz, 12.2 Hz, 8.9 Hz, 6.8 Hz, 6.5 Hz, 1F), –133.5 (ddd, J = 265.5 Hz, 17.0 Hz, 12.4 Hz, 1F), –140.0 (ddd, J = 299.1 Hz, 52.8 Hz, 12.2 Hz, 1F), –144.5 (m, J = 299.1 Hz, 53.0 Hz, 12.4 Hz, 6.8 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{16}H_{24}F_4OSi$ + H: 337.1611, Found: 337.1607.

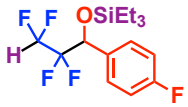


(2,2,3,3-tetrafluoro-1-(*o*-tolyl)propoxy)triethylsilane (4d): The general procedure A was followed with **1d** (120.2 mg, 1.0 mmol), and the reaction mixture was stirred for 3 h. Purification by silica gel column chromatography gave **4d** (199.2 mg, 59%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt,

δ/ppm): 0.52 (m, *J* = 7.9 Hz, 6H), 0.87 (t, *J* = 7.9 Hz, 9H), 2.37 (s, 3H), 5.34 (br, *J* = 18.4 Hz, 1H), 6.07 (br, *J* = 54.1 Hz, 53.2 Hz, 10.3 Hz, 1H), 7.18 (br, 1H), 7.24–7.29 (2H), 7.57 (br, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.6 (s), 6.5 (s), 19.5 (d, *J* = 2.5 Hz), 68.7(dd, *J* = 30.1 Hz, 25.5 Hz), 109.7 (dddd, *J* = 252.4 Hz, 247.2 Hz, 27.1 Hz, 5.5 Hz), 115.6 (dddd, *J* = 253.0 Hz, 252.9 Hz, 21.0 Hz, 2.4 Hz), 125.9 (s), 128.9 (s), 129.1 (s), 130.4 (s), 133.8 (s), 136.2 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –131.1 (br, *J* = 266.7 Hz, 1F), –133.4 (br, *J* = 266.7 Hz, 1F), –139.2 (m, *J* = 298.0 Hz, 53.2 Hz, 1F), –145.5 (m, *J* = 298.0 Hz, 54.1 Hz, 11.2 Hz, 9.0 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{16}H_{24}F_4OSi$ + H: 337.1611, Found: 337.1605.

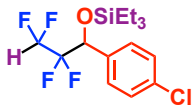


(2,2,3,3-tetrafluoro-1-mesitylpropoxy)triethylsilane (4e): The general procedure A was followed with **1e** (148.2 mg, 1.0 mmol), and the reaction mixture was stirred for 3 h. Purification by silica gel column chromatography gave **4e** (169.7 mg, 47%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.53 (q, *J* = 7.9 Hz, 6H), 0.85 (t, *J* = 7.9 Hz, 9H), 2.26 (s, 3H), 2.31 (s, 3H), 2.48 (d, *J* = 2.6 Hz, 3H), 5.50 (m, *J* = 24.0 Hz, 5.2 Hz, 2.2 Hz, 1H), 6.08 (m, *J* = 54.5 Hz, 53.0 Hz, 10.6 Hz, 1.0 Hz, 1H), 6.81 (s, 1H), 6.86 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.5 (s), 6.6 (s), 20.9 (d, *J* = 3.7 Hz), 21.0 (s), 21.2 (d, *J* = 10. 3 Hz), 69.7 (m, *J* = 32.3 Hz, 23.0 Hz), 109.7 (dddd, *J* = 253.4 Hz, 246.5 Hz, 27.0 Hz, 6.2 Hz), 116.8 (dddd, *J* = 256.5 Hz, 251.6 Hz, 20.8 Hz, 5.5 Hz), 128.2 (s), 129.2 (s), 131.7 (s), 137.2 (s), 138.2 (s), 139.8(s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –129.0 (m, *J* = 269.6 Hz, 11.4 Hz, 10.6 Hz, 1F), –130.6 (m, *J* = 269.6 Hz, 24.0 Hz, 11.1 Hz, 1F), –139.2 (m, *J* = 297.0 Hz, 53.0 Hz, 11.4 Hz, 1F), –146.7 (m, *J* = 297.0 Hz, 54.5 Hz, 11.1 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{18}H_{28}F_4OSi$: 364.1846, Found: 364.1850.

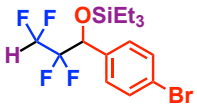


(2,2,3,3-tetrafluoro-1-(4-fluorophenyl)propoxy)triethylsilane (4f): The general procedure A was followed with **1f** (124.1 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4f** (256.4 mg, 75%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.53 (m, *J* = 8.0 Hz, 6H), 0.88 (t, *J* = 8.0 Hz, 9H), 4.97 (ddd, *J* = 17.1 Hz, 6.0 Hz, 2.0 Hz, 1H), 5.99 (dddd, *J* = 54.3Hz, 52.9 Hz, 9.2 Hz, 2.3 Hz, 1H), 7.07 (dd, *J* = 8.6 Hz, 6.7 Hz, 2H), 7.41 (dd, *J* = 8.6 Hz, 5.7 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.5 (s), 6.5 (s), 72.5 (dd, *J* = 30.6 Hz, 23.1 Hz), 109.4 (dddd, *J* = 252.0 Hz, 248.1 Hz, 28.0 Hz, 4.2 Hz), 114.7 (dddd, *J* = 254.5

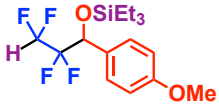
Hz, 253.5 Hz, 23.8 Hz, 2.5 Hz), 115.2 (s), 115.4 (s), 130.0 (d, J = 8.3 Hz), 131.2 (d, J = 2.8 Hz), 162.0 (s), 164.5(s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –116.3 (m, J = 6.7 Hz, 5.7 Hz, 1F), –131.5 (br, J = 266.9 Hz, 6.6 Hz, 6.0 Hz, 1F), –134.8 (ddd, J = 266.9 Hz, 17.1 Hz, 14.1 Hz, 1F), –139.7 (ddd, J = 299.9 Hz, 52.9 Hz, 12.1 Hz, 1F), –143.3 (m, J = 299.9 Hz, 54.3 Hz, 14.1 Hz, 6.6 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{15}H_{21}F_5OSi$: 340.1282, Found: 340.1359.



(2,2,3,3-tetrafluoro-1-(4-chlorophenyl)propoxy)triethylsilane (4g): The general procedure A was followed with **1g** (140.6 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4g** (139.0 mg, 39%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.54 (q, J = 8.0 Hz, 6H), 0.88 (t, J = 8.0 Hz, 9H), 4.96 (ddd, J = 16.9 Hz, 6.0 Hz, 2.0 Hz, 1H), 5.99 (dddd, J = 53.2 Hz, 52.5 Hz, 9.2 Hz, 2.0 Hz, 1H), 7.36–7.37 (4H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.6 (s), 6.6 (s), 72.6 (dd, J = 30.5 Hz, 23.7 Hz), 109.5 (dddd, J = 252.3 Hz, 248.1 Hz, 28.3 Hz, 4.2 Hz), 114.8 (dddd, J = 255.6 Hz, 252.1 Hz, 22.3 Hz, 2.3 Hz), 128.6 (s), 129.6 (s), 134.0 (s), 135.2 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.2 (m, J = 267.6 Hz, 11.4 Hz, 9.2 Hz, 6.8 Hz, 6.0 Hz, 1F), –133.5 (ddd, J = 267.6 Hz, 16.9 Hz, 10.8 Hz, 1F), –139.7 (ddd, J = 300.2 Hz, 52.5 Hz, 11.4 Hz, 1F), –144.4 (m, J = 300.2 Hz, 53.2 Hz, 10.8 Hz, 6.8 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{15}H_{22}ClF_4OSi$: 357.1065, Found: 357.1058.

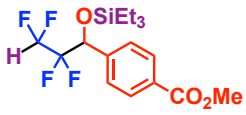


An attempt at preparation of (2,2,3,3-tetrafluoro-1-(4-bromophenyl)propoxy)triethylsilane (4h): The general procedure B was followed with **1h** (18.5 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the target compound was not generated.

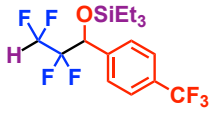


(2,2,3,3-tetrafluoro-1-(4-methoxyphenyl) propoxy)triethylsilane (4i): The general procedure A was followed with *p*-anisaldehyde (**1i**: 136.2 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4i** (155.8 mg, 55%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.53 (m, J = 7.9 Hz, 6H), 0.88 (t, J = 7.9 Hz, 9H), 3.82 (s, 3H), 4.93 (ddd, J = 17.1Hz, 6.5 Hz, 2.0 Hz, 1H), 5.98 (dddd, J = 53.8 Hz, 53.0 Hz, 9.1 Hz, 2.3 Hz, 1H),

6.91 (d, J = 8.8 Hz, 2H), 7.34 (d, J = 8.8 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.7 (s), 6.6 (s), 55.3 (s), 72.8 (dd, J = 30.2 Hz, 23.3 Hz), 109.7 (dddd, J = 251.8 Hz, 247.3 Hz, 27.9 Hz, 3.8 Hz), 113.7 (s), 115.0 (dddd, J = 255.2 Hz, 251.7 Hz, 22.3 Hz, 2.3 Hz), 127.5 (s), 129.5 (s), 166.0 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.9 (m, J = 266.9 Hz, 12.6 H, 9.1 Hz, 6.5 Hz, 6.3 Hz, 1F), –133.8 (ddd, J = 266.9 Hz, 17.1 Hz, 14.5 Hz, 1F), –139.7 (ddd, J = 300.1 Hz, 53.0 Hz, 12.6 Hz, 1F), –144.4 (m, J = 300.1 Hz, 53.8 Hz, 14.5 Hz, 6.3 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{16}H_{24}F_4O_2Si$: 352.1482, Found: 352.1479.

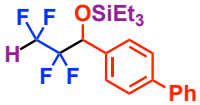


(2,2,3,3-tetrafluoro-1-(4-methoxycarbonylphenyl)propoxy)triethylsilane (4j): The general procedure A was followed with methyl **1j** (164.2 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4j** (325.3 mg, 86%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.55 (q, J = 8.0 Hz, 6H), 0.87 (t, J = 8.0 Hz, 9H), 3.92 (s, 3H), 5.04 (ddd, J = 16.8 Hz, 6.1 Hz, 1.7 Hz, 1H), 5.99 (dddd, J = 54.4 Hz, 53.2 Hz, 8.8 Hz, 2.0 Hz, 1H), 7.51 (d, J = 8.0 Hz, 2H), 7.30 (d, J = 8.0 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.6 (s), 6.5 (s), 52.3 (s), 72.9 (dd, J = 30.2 Hz, 23.0 Hz), 109.4 (ddd, J = 252.5 Hz, 248.3 Hz, 28.3 Hz, 4.1 Hz), 114.7 (ddd, J = 255.4 Hz, 253.4 Hz, 22.4 Hz, 2.6 Hz), 128.9 (s), 129.5 (s), 131.0 (s), 140.4(s), 166.8(s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –129.9 (m, J = 269.7 Hz, 11.6 Hz, 8.8 Hz, 6.8 Hz, 6.1 Hz, 1F), –133.1 (ddd, J = 269.7 Hz, 16.8 Hz, 12.7 Hz, 1F), –139.6 (ddd, J = 300.5 Hz, 53.2 Hz, 11.6 Hz, 1F), –144.2 (m, J = 300.5 Hz, 54.4 Hz, 12.7 Hz, 6.8 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{17}H_{24}F_4O_3Si$ + H: 381.1509, Found: 381.1507.

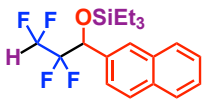


(2,2,3,3-tetrafluoro-1-(4-trifluoromethylphenyl)propoxy)triethylsilane (4k): The general procedure A was followed with **1k** (136.1 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4k** (305.7 mg, 78%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.56 (m, J = 8.0 Hz, 6H), 0.88 (t, J = 8.0 Hz, 9H), 5.06 (ddd, J = 16.8 Hz, 5.9 Hz, 1.9 Hz, 1H), 6.01 (dddd, J = 53.7 Hz, 53.2 Hz, 8.8 Hz, 2.3 Hz, 1H), 7.56 (d, J = 8.0 Hz, 2H), 7.65 (d, J = 8.0 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.6 (s), 6.5 (s), 72.8

(dd, J = 30.2 Hz, 23.3 Hz), 109.2 (dddd, J = 251.8 Hz, 248.0 Hz, 28.4 Hz, 3.6 Hz), 111.9 (dddd, J = 255.1 Hz, 253.4 Hz, 22.4 Hz, 1.5 Hz), 124.1 (t, J = 272.1 Hz), 125.3 (q, J = 4.0 Hz), 128.6 (s), 131.5 (q, J = 32.4 Hz), 139.5 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –65.3 (s, 3F), –129.8 (m, J = 268.1 Hz, 10.9 Hz, 8.8 Hz, 6.8 Hz, 5.9 Hz, 1F), –133.3 (ddd, J = 268.1 Hz, 16.8 Hz, 11.1 Hz, 1F), –139.7 (ddd, J = 298.0 Hz, 53.2 Hz, 10.9 Hz, 1F), –144.3 (m, J = 298.0 Hz, 53.7 Hz, 11.1 Hz, 6.8 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{16}H_{21}F_7OSi$: 390.1250, Found: 390.1251.

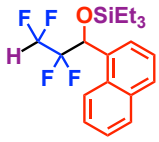


(2,2,3,3-tetrafluoro-1-(biphenyl)propoxy)triethylsilane (4l): The general procedure A was followed with **1l** (182.2 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4l** (282.9 mg, 71%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.59 (q, J = 7.9 Hz, 6H), 0.91 (t, J = 7.9 Hz, 9H), 5.05 (ddd, J = 17.0 Hz, 6.5 Hz, 1.6 Hz, 1H), 6.03 (dddd, J = 54.5 Hz, 53.1 Hz, 8.8 Hz, 2.2 Hz, 1H), 7.37 (t, J = 7.5 Hz, 1H), 7.46–7.51 (4H), 7.58–7.69 (4H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.7 (s), 6.6 (s), 73.1 (dd, J = 30.1 Hz, 23.1 Hz), 109.6 (dddd, J = 251.1 Hz, 248.1 Hz, 27.8 Hz, 3.8 Hz), 115.0 (dddd, J = 257.0 Hz, 252.0 Hz, 22.4 Hz, 2.5 Hz), 127.0 (s), 127.3 (s), 127.7 (s), 128.7 (s), 128.9 (s), 134.4 (s), 140.6 (s), 142.1 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.6 (m, J = 266.8 Hz, 12.1 Hz, 8.8 Hz, 7.3 Hz, 6.5 Hz, 1F), –133.4 (ddd, J = 266.8 Hz, 17.0 Hz, 12.5 Hz, 1F), –139.8 (ddd, J = 298.8 Hz, 53.1 Hz, 12.1 Hz, 1F), –144.4 (m, J = 298.8 Hz, 54.5 Hz, 12.5 Hz, 7.3 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{21}H_{26}F_4O_2Si$: 398.1689, Found: 398.1687.

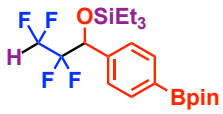


(2,2,3,3-tetrafluoro-1-(2-naphtyl)propoxy)triethylsilane (4m): The general procedure A was followed with **1m** (156.2 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4m** (218.0 mg, 59%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.59 (m, J = 8.0 Hz, 6H), 0.91 (t, J = 8.0 Hz, 9H), 5.20 (ddd, J = 16.9 Hz, 6.6 Hz, 1.8 Hz, 1H), 5.97 (dddd, J = 53.2 Hz, 52.6 Hz, 8.7 Hz, 2.2 Hz, 1H), 7.49–7.58 (2H), 7.6 (d, J = 8.6 Hz, 1H), 7.86–7.92 (4H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.8 (s), 6.7 (s), 73.5 (dd, J = 30.0 Hz, 23.2 Hz), 109.7 (dddd, J = 252.0 Hz, 248.4 Hz, 28.6 Hz, 3.8 Hz), 115.2 (dddd, J = 255.4 Hz, 252.9 Hz, 22.3 Hz, 1.5 Hz), 125.6 (s), 126.6 (s), 126.8 (s), 128.0 (s), 128.2 (s), 128.4 (s), 133.0 (s), 133.1 (s), 134.0 (s), One aromatic-C could not be detected due to the overlap. **^{19}F NMR** (376 MHz, in

$CDCl_3$, rt, δ/ppm): –130.4 (m, *J* = 267.1 Hz, 11.8 Hz, 8.7 Hz, 6.9 Hz, 6.6 Hz, 1F), –133.2 (ddd, *J* = 267.1 Hz, 16.9 Hz, 11.0 Hz, 1F), –139.7 (ddd, *J* = 299.7 Hz, 52.6 Hz, 11.8 Hz, 1F), –144.4 (m, *J* = 299.7 Hz, 53.2 Hz, 11.0 Hz, 6.9 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{19}H_{24}F_4OSi$: 372.1533, Found: 372.1531.

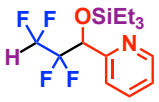


(2,2,3,3-tetrafluoro-1-(1-naphtyl)propoxy)triethylsilane (4n): The general procedure A was followed with **1n** (156.2 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4n** (194.5 mg, 52%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.52 (m, *J* = 7.9 Hz, 6H), 0.84 (t, *J* = 7.9 Hz, 9H), 5.89 (br, 1H), 6.11 (dddd, *J* = 54.3 Hz, 53.4 Hz, 1H), 7.46–7.60 (3H), 7.79 (br, 1H), 7.88 (br, 1H), 7.90 (br, 1H), 8.07 (br, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.6 (s), 6.6 (s), 68.3 (br), 109.8 (dddd, *J* = 252.5 Hz, 247.5 Hz, 32.7 Hz, 5.0 Hz, m), 115.5 (dddd, *J* = 255.2 Hz, 254.0 Hz, 21.2 Hz), 123.2 (br), 125.1 (s), 125.8 (s), 126.6 (s), 127.7 (s), 129.0 (s), 129.9 (s), 131.3 (s), 131.5 (s), 133.7 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –129.7 (br, *J* = 264.1 Hz, 1F), –133.0 (br, *J* = 264.1 Hz, 1F), –138.9 (ddd, *J* = 299.4 Hz, 53.4 Hz, 6.2 Hz, 1F), –144.7 (m, *J* = 299.4 Hz, 54.3 Hz, 9.6 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{19}H_{24}F_4OSi$: 372.1533, Found: 372.1531.

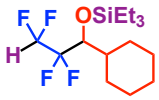


4,4,5,5-tetrafluoro-1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)pentan-1-one (2o): The general procedure A was followed with **1o** (232.1 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4o** (265.4 mg, 83%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.52 (m, *J* = 7.8 Hz, 6H), 0.87 (t, *J* = 7.8 Hz, 9H), 1.35 (s, 12H), 4.99 (ddd, *J* = 16.6 Hz, 6.5 Hz, 1.6 Hz, 1H), 5.97 (dddd, *J* = 53.6 Hz, 53.0 Hz, 8.8 Hz, 2.4 Hz, 1H), 7.42 (d, *J* = 7.7 Hz, 2H), 7.81 (d, *J* = 7.7 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 4.7 (s), 6.6 (s), 25.0 (s), 25.1 (s), 73.3 (dd, *J* = 29.6 Hz, 23.2 Hz), 84.1 (s), 109.5 (dddd, *J* = 251.7 Hz, 247.8 Hz, 28.4 Hz, 3.8 Hz), 114.9 (dddd, *J* = 256.1 Hz, 252.7 Hz, 22.4 Hz, 2.3 Hz), 127.6 (s), 134.7 (s), 138.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.5 (m, *J* = 267.3 Hz, 12.2 Hz, 8.8 Hz, 7.0 Hz, 6.5 Hz, 1F), –133.2 (ddd, *J* = 267.3 Hz, 16.6 Hz, 11.0 Hz, 1F), –139.8 (ddd, *J* = 300.1 Hz,

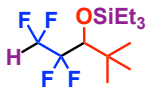
53.0 Hz, 12.2 Hz, 1F), –144.1 (m, *J* = 300.1 Hz, 53.6 Hz, 11.0 Hz, 7.0 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{21}H_{34}BF_4O_3Si$: 449.2306, Found: 449.2311.



An attempt at preparation of (2,2,3,3-tetrafluoro-1-(2-pylidine)propoxy)triethylsilane (4p): The general procedure B was followed with **1p** (10.7 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the target compound was not generated.

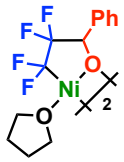


(2,2,3,3-tetrafluoro-1-cyclohexylepropoxy)triethylsilane (4q): The general procedure A was followed with **1q** (112.2 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4q** (157.0 mg, 48%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.66 (q, *J* = 7.9 Hz, 6H), 0.98 (t, *J* = 7.9 Hz, 9H), 1.08–1.25 (5H), 1.68–1.78 (6H), 3.80 (m, *J* = 12.7 Hz, 6.3 Hz, 3.3 Hz, 1H), 5.88 (dddd, *J* = 54.5 Hz, 53.1 Hz, 6.4 Hz, 4.9 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 5.1 (s), 6.9 (s), 26.4 (s), 26.5 (s), 26.7 (s), 27.7 (s), 30.3 (d, *J* = 3.1 Hz), 39.9 (s), 75.1 (dd, *J* = 25.3 Hz, 23.2 Hz), 109.6 (dddd, *J* = 250.8 Hz, 248.8 Hz, 36.2 Hz, 31.6 Hz), 116.8 (dddd, *J* = 254.7 Hz, 251.3 Hz, 23.4 Hz, 1.4 Hz). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –126.3 (m, *J* = 269.2 Hz, 9.5 Hz, 6.4 Hz, 4.2 Hz, 3.3 Hz 1F), –128.9 (m, *J* = 269.2 Hz, 12.7 Hz, 9.5 Hz, 1F), –140.5 (ddd, *J* = 298.5 Hz, 53.1 Hz, 9.5 Hz, 3.1 Hz, 1F), –142.7 (m, *J* = 298.5 Hz, 54.5 Hz, 9.5. Hz, 4.2 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{15}H_{28}F_4OSi$ + H: 329.1924, Found: 329.1922.

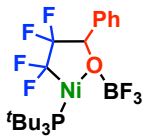


(2,2,3,3-tetrafluoro-1-(*tert*-butyl)propoxy)triethylsilane (4t): The general procedure A was followed with pivalaldehyde (**1t**: 86.1 mg, 1.0 mmol), and the reaction mixture was stirred for 1 h. Purification by silica gel column chromatography gave **4t** (43.8 mg, 14%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.69 (q, *J* = 7.9 Hz, 6H), 0.98 (t, 7.9 Hz, 9H), 1.03 (s, 9H), 3.72 (ddd, *J* = 19.4 Hz, 7.8 Hz, 2.5 Hz, 1H), 5.99 (dddd, *J* = 54.9 Hz, 52.4 Hz, 9.4 Hz, 2.4 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 5.4 (s), 7.1 (s), 27.2 (dd, *J* = 2.3 Hz, 2.3 Hz), 35.5 (s), 78.3 (dd, *J* = 27.0 Hz, 22.9 Hz), 109.6 (dddd, *J* = 251.7 Hz, 248.0 Hz, 27.0 Hz, 3.8 Hz), 117.7 (dddd, *J* = 258.0 Hz,

256.3 Hz, 21.5 Hz, 2.3 Hz). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –130.4 (br, J = 269.0 Hz, 1F), –133.3 (ddd, J = 269.0 Hz, 19.4 Hz, 11.1 Hz. 1F), –139.7 (m, J = 294.1 Hz, 52.4 Hz, 11.2 Hz, 1F), –144.2 (m, J = 294.1 Hz, 54.9 Hz, 11.1 Hz, 5.4 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{13}H_{26}F_4OSi$ + H: 303.1767, Found: 303.1763.

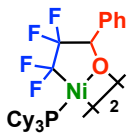


Preparation of [(CF_2CF_2CHPhO)Ni(THF)]$_2$ (*syn*-III): A hexane solution (6.0 mL) of Ni(cod)$_2$ (275.1 mg, 1.0 mmol) and P^{t}Bu$_3$ (202.3 mg, 1.0 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). Then, TFE (3.5 atm) was charged into the reactor. The reaction mixture was stirred at room temperature for 3 h. After all volatiles were removed under reduced pressure, the residue was washed with hexane followed by recrystallization from THF and pentane to afford a single crystal of ***syn*-III** as a purple solid (302.8 mg, 90%). **^{1}H NMR** (400 MHz, in C_6D_6, rt, δ/ppm): 0.38 (br, J = 6.2 Hz, 4H, -OCH_2CH_2-), 0.49 (br, J = 6.2 Hz, 4H, -OCH_2CH_2-), 2.85 (br, J = 6.0 Hz, 4H, -OCH_2-), 3.14 (br, J = 6.0 Hz, 4H, -OCH_2-), 3.89 (d, J = 20.5 Hz, 2H, -$COCH$Ph-), 6.89 – 6.96 (6H, aromatic–*H*), 7.28 (d, J = 7.0 Hz, 4H, aromatic–*H*). **^{13}C{^{1}H} NMR** (100 MHz, in C_6D_6, rt, δ/ppm): 23.5 (s, -OCH_2CH_2-), 72.1 (s, -OCH_2-), 75.6 (dd, J = 22.4 Hz, 29.7 Hz, -*CO*-), 136.2 (s, aromatic–*C*). Resonances attributable to the CF_2CF_2 moiety could not be detected due to multiple ^{13}C–^{19}F couplings and aromatic–C also could not be detected due to the overlap with C_6D_6. **^{19}F NMR** (376 MHz, in C_6D_6, rt, δ/ppm): −102.0 (d, J = 219.0 Hz, 2F, α-CF_2-), –125.4 (dd, J = 219.0 Hz, 17.4 Hz, 2F, α-CF_2-), –130.1 (d, J = 235.5 Hz, 2F, β-CF_2), –134.4 (ddd, J = 235.5 Hz, 20.5 Hz, 17.4 Hz, 2F, β-CF_2-). **Anal. Calcd** for $C_{26}H_{28}F_8Ni_2O_4$: C, 46.43; H, 4.19. Found: C, 46.59; H, 4.47. **X-ray data** for the complex ***syn*-III**. M = 673.88, platelet, red, monoclinic, $P2_1/n$, a = 23.3852(5) Å, b = 10.22746(18) Å, c = 29.4916(5) Å, β = 102.3212 (7), V = 6891.1(2) Å^3, Z = 4, Dcalcd = 1.624 g/cm^3, T = –150 °C, R_1 (wR_2) = 0.0604 (0.1246).



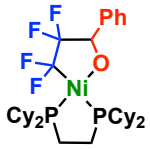
Preparation of (CF_2CF_2CHPhO)Ni(P^{t}Bu$_3$)(BF_3) (IV): A benzene solution (5.0 mL) of ***syn*-III** (67.4 mg, 0.10 mmol), P^{t}Bu$_3$ (40.5 mg, 0.20 mmol), and BF_3·Et_2O (25.2 mg, 0.20 mmol) was transferred

into an pressure-tight reactor. The reaction mixture was stirred at room temperature for 6 h. All volatiles were removed under reduced pressure, and the crude product was washed with hexane, followed by recrystallization from benzene and pentane to afford a single crystal of **IV** as a purple solid (106.2 mg, 99%). **^{1}H NMR** (400 MHz, in C_6D_6, rt, δ/ppm): 0.88 (d, J = 13.0 Hz, 27H, -^{t}Bu), 5.44 (m, J = 18.0 Hz, 1H, -OC*H*Ph), 7.04 (d, J = 7.0 Hz, 1H, aromatic-*H*), 7.15 (dd, J = 7.0 Hz, 2H, aromatic-*H*), 7.6 (d, J = 7.0 Hz, 2H, aromatic-*H*). **^{13}C{^{1}H} NMR** (100 MHz, in C_6D_6, rt, δ/ppm): 30.4 (s, -P^{t}Bu$_3$), 38.1 (d, J = 12.9 Hz, -P^{t}Bu$_3$), 76.3 (dd, J = 32.3 Hz, 22.7 Hz, -O*C*HPh), 128.7 (s, aromatic-*C*), 129.3 (s, aromatic-*C*), 133.5 (s, aromatic-*C*). Resonances attributable to the CF_2CF_2 moiety could not be detected due to multiple ^{13}C–^{19}F couplings, and resonances attributable to the aromatic-C could not be detected due to the overlap with C_6D_6. **^{19}F NMR** (376 MHz, in C_6D_6, rt, δ/ppm): –83.1 (dd, J = 165.7 Hz, 15.9 Hz, 1F, α-C*F*$_2$-), –94.0 (m, J = 165.7 Hz, 1F, α-C*F*$_2$-), –130.1 (m, J = 246.7 Hz, 1F, β-C*F*$_2$-), –123.8 (ddd, J = 246.7 Hz, 18.0 Hz, 1F, β-C*F*$_2$-), –148.4 (s, 3F, -B*F*$_3$). **^{31}P NMR** (162 MHz, in C_6D_6, rt, δ/ppm): 59.2 (d, J = 29.2 Hz, 1P, -*P*^{t}Bu). **^{11}B NMR** (128 MHz, in C_6D_6, rt, δ/ppm): 0.42 (s, 1B, -*B*F$_3$). **Anal. Calcd** for $C_{21}H_{33}BF_7NiOP$: C, 47.15; H, 6.22. Found: C, 47.10; H, 6.37. **X-ray data** for the complex **IV**. M = 534.96, block, purple, orthorhombic, $P2_12_12_1$, a = 8.59252(16) Å, b = 14.9121(3) Å, c = 19.1875(5) Å, V = 2458.54(8) Å^3, Z = 4, Dcalcd = 1.445 g/cm^3, T = –150 °C, R_1 (wR_2) = 0.0213 (0.0556).



Preparation of [(CF$_2$CF$_2$CHPhO)Ni(PCy$_3$)]$_2$ (*syn*-V): A benzene solution (5.0 mL) of ***syn*-III** (67.4 mg, 0.10 mmol) and PCy$_3$ (56.1 mg, 0.20 mmol) was transferred into a pressure-tight reactor. The reaction mixture was stirred at room temperature for 3 h. All volatiles were removed under reduced pressure, and the crude product was washed with hexane to afford ***syn*-6** as a purple solid (105.8 mg, 98%). The single crystals of ***syn*-V** was prepared by recrystallization from THF and hexane for single-crystal X-ray diffraction analysis. **^{1}H NMR** (400 MHz, in C_6D_6, rt, δ/ppm): 1.02–2.70 (66H, -PCy$_3$), 4.30 (d, J = 17.6 Hz, 2H, -OC*H*Ph), 7.39 (dd, J = 7.6 Hz, 7.2 Hz, 4H, aromatic-*H*), 8.38 (br, 4H, aromatic-*H*), Resonances attributable to the aromatic-H could not be detected due to the overlap with C_6D_5H. **^{13}C{^{1}H} NMR** (100 MHz, in C_6D_6, rt, δ/ppm): 26.7 (s, -PCy$_3$), 28.4 (dd, J = 22.8 Hz, 9.9 Hz, -PCy$_3$), 26.7 (d, J = 35.4 Hz, -PCy$_3$), 33.8 (d, J = 19.0 Hz, -PCy$_3$), 76.7 (dd, J = 23.9 Hz, 27.3 Hz, -O*C*HPh), 128.7 (s, aromatic-*C*), 138.9 (s, aromatic-*C*). Resonances attributable to the CF_2CF_2 moiety could not be detected due to multiple ^{13}C–^{19}F couplings and resonances attributable to the aromatic-C

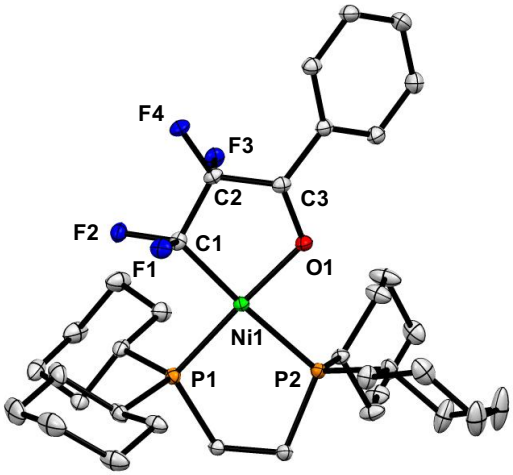
could not be detected due to the overlap with C_6D_6. **^{19}F NMR** (376 MHz, in C_6D_6, rt, δ/ppm): –98.9 (dd, *J* = 220.6 Hz, 9.7 Hz, 2F, α-C*F*$_2$-), –105.2 (m, *J* = 220.6 Hz, 2F, α-C*F*$_2$-), –122.6 (m, *J* = 234.0 Hz, 2F, β-C*F*$_2$-), –129.2 (ddd, *J* = 234.0 Hz, 17.6 Hz, 2F, β-C*F*$_2$-). **^{31}P NMR** (162 MHz, in C_6D_6, rt, δ/ppm): 30.8 (m, *J* = 9.7 Hz, 2P, -*P*Cy$_3$). **Anal. Calcd** for $C_{54}H_{78}F_8Ni_2O_2P_2$: C, 59.47; H, 7.21. Found: C, 59.44; H, 7.51. **X-ray data** for the complex ***syn*-V**. M = 1090.54, block, red, monoclinic, *P*2$_1$/c, *a* = 16.08339(17) Å, *b* = 20.4723(2) Å, *c* = 19.8003(2) Å, β = 113.0861(13), V = 5997.42(13) Å^3, Z = 4, Dcalcd = 1.208 g/cm^3, T = –150 °C, R_1 (*w*R_2) = 0.0437 (0.1166).



Preparation of (CF$_2$CF$_2$CHPhO)Ni(DCPE) (VI): A benzene solution (5.0 mL) of ***syn*-III** (67.4 mg, 0.10 mmol) and DCPE (84.5 mg, 0.20 mmol) was transferred into a pressure-tight reactor. The reaction mixture was stirred at room temperature for 3 h. All volatiles were removed under reduced pressure, and the crude product was washed with hexane to afford **VI** as a yellow solid (114.7 mg, 83%). The single crystals of **VI** was prepared by recrystallization from THF and pentane for single-crystal X-ray diffraction analysis. **^{1}H NMR** (400 MHz, in C_6D_6, rt, δ/ppm): 0.91–2.11 (44H, aliphatic-*H*), 2.32 (dd, *J* = 68.3 Hz, 2H, -PCH$_2$C*H*$_2$P-), 2.67 (dd, *J* = 68.3 Hz, 2H, -PC*H*$_2$CH$_2$P-), 5.55 (br, *J* = 21.0 Hz, 1H, -OC*H*Ph), 7.18 (t, *J* = 7.7 Hz, 1H, aromatic-*H*), 7.32 (dd, *J* = 7.7 Hz, 7.5 Hz, 2H, aromatic-*H*), 7.89 (d, *J* = 7.5 Hz, 2H, aromatic-*H*). **^{13}C{^{1}H} NMR** (100 MHz, in C_6D_6, rt, δ/ppm): 17.8 (dd, *J* = 21.3 Hz, 10.1 Hz, -DCPE), 23.5 (dd, *J* = 26.0 Hz, 20.1 Hz, -DCPE), 26.3 (d, *J* = 9.7 Hz, -DCPE), 26.5 (d, *J* = 3.4 Hz, -DCPE), 27.3 (dd, *J* = 15.5 Hz, 9.2 Hz, -DCPE), 27.2 (d, *J* = 11.9 Hz, -DCPE), 27.6 (dd, *J* = 12.5 Hz, 6.4 Hz, -DCPE), 27.8 (s, -DCPE), 28.6 (d, *J* = 2.5 Hz, -DCPE), 29.0 (br, -DCPE), 29.2 (dd, *J* = 11.0 Hz, 4.9 Hz, -DCPE), 29.3 (d, *J* = 10.2 Hz, -DCPE), 29.7 (d, *J* = 24.2 Hz, 4.3 Hz, -DCPE), 31.4 (br, -DCPE), 33.1 (d, *J* = 18.6 Hz, -DCPE), 34.0 (d, *J* = 17.0 Hz, -DCPE), 34.6 (d, *J* = 17.0 Hz, -DCPE), 35.9 (d, *J* = 23.3 Hz, -DCPE), 78.6 (m, *J* = 24.8 Hz, -O*C*HPh), 127.2 (s, aromatic-*C*), 127.7 (s, aromatic-*C*), 128.7 (s, aromatic-*C*), 142.9 (s, aromatic-*C*). Resonances attributable to the CF_2CF_2 moiety could not be detected due to multiple ^{13}C–^{19}F couplings. **^{19}F NMR** (376 MHz, in C_6D_6, rt, δ/ppm): –100.9 (m, *J* = 255.0 Hz, 1F, α-C*F*$_2$-), –109.5 (m, *J* = 255.0 Hz, 20.4 Hz, 1F, α-C*F*$_2$-), –130.2 (d, *J* = 229.4 Hz, 1F, β-C*F*$_2$-), –135.3 (ddd, *J* = 229.4 Hz, 21.0 Hz, 20.4 Hz, 1F, β-C*F*$_2$-). **^{31}P NMR** (162 MHz, in C_6D_6, rt, δ/ppm): 72.9 (dd, *J* = 21.6 Hz, 1P), 62.2 (m, *J* = 21.6 Hz, 1P). **Anal. Calcd** for $C_{35}H_{54}F_4NiOP_2$: C, 61.15; H, 7.92. Found: C, 61.28; H, 8.13. **X-ray data** for the complex **VI**. M = 687.45, platelet, yellow, monoclinic, *C*2/n, *a* = 25.3155(5) Å, *b* = 16.6122(3) Å, *c* = 17.9503(3) Å, β

= 95.2001 (7), V = 7517.9(2) Å^3, Z = 8, Dcalcd = 1.215 g/cm^3, T = –150 °C, R_1 (wR_2) = 0.0327 (0.0847).

Figure 3.3. ORTEP representations of VI with thermal ellipsoids at the 30% probability; selected hydrogen atoms have been omitted for clarity.



Selected bond lengths [Å] and angles [°]	
C1-C2	1.528(2)
C2-C3	1.518(2)
C3-O1	1.3496(19)
Ni1-C1	1.9215(16)
Ni1-O1	1.8708(11)
C1-Ni1-O1	86.68(6)
C1-Ni1-P1	96.03(5)
O1-Ni1-P2	89.83(4)
P1-Ni1-P2	87.455(17)
	<sum> <360.00>

$R_1(wR_2)$ = 0.0327 (0.0847)

Stoichiometric reactions of the oxa-nickelacycles with Et_3SiH: A C_6D solution (0.5 mL) of a given oxa-nickelacycle (either 0.01 mmol or 0.005 mmol), a given additive (either 0 or 0.01 mmol), and Et_3SiH (0.10 mmol) was transferred into a sealed NMR tube. The reaction mixture was remained at room temperature for a given time. The yield of **4a** was determined by gas chromatography using dodecane as the internal standard.

Catalytic Reactions with the oxa-nickelacycles: A C_6D_6 solution (0.5 mL) of a given oxa-nickelacycle (either 0.01 mmol or 0.005 mmol), a given additive (either 0 or 0.01 mmol), **1a** (0.10 mmol), and Et_3SiH (0.11 mmol) was transferred into a pressure-tight NMR tube. Then, TFE (3.5 atm, >0.30 mmol) was charged into the reaction tube. The reaction tube was remained at room temperature for 9 h. The yield of **4a** was determined by gas chromatography using dodecane as an internal standard.

Stoichiometric reactions without the isolation of the oxa-nickelacycles: The reaction was conducted with a pressure-tight NMR tube (Wilmad-LabGlass, 524-PV-7). A C_6D_6 solution (0.5 mL) of $Ni(cod)_2$ (8.3 mg, 0.03 mmol), P^tBu_3 (6.7 mg, 0.03 mmol), **1a** (0.30 mmol) was exposed to TFE (3.5 atm, >0.30 mmol). The reaction mixture was remained at room temperature for 3 h. After the unreacted TFE was purged from the reactor, Et_3SiH was added at room temperature for 5 h. (caution:

The reaction mixture must be handle in a well-ventilated fume hood.) The yield of **4a** was determined by gas chromatography using dodecane as the internal standard.

Preparation of trifuorosilylenolether (6b): A THF solution (0.3 mL) of $^{i}Pr_2NH$ (55.7 mg, 0.55 mmol) was added to a hexane solution of ^{n}BuLi (1.6 M, 0.55 mmol) at –78 ºC, and the reaction mixture was stirred at 0 ºC for 1 h to prepare lithium diisopropyl amide. Then, a THF solution (0.35 mL) of **4b** was added to the reaction mixture and stirred at 0 ºC for 2 h. After quenched under air, the crude product was further purified by silica gel column chromatography (hexane:AcOEt = 99:1) to afford trifluoro silyl enol ether (**6b**: 142.3, 90%) as yellow liquid. The chemical shifts of **6b** were consistent with those reported in the literature.[12]

Preparation of organic silicon compound (7b): A THF solution (0.3 mL) of $^{i}Pr_2NH$ (55.7 mg, 0.55 mmol) was added to a hexane solution of ^{n}BuLi (1.6 M, 0.55 mmol) at –78 ºC, and the reaction mixture was stirred at 0 ºC for 1 h to prepare lithium diisopropyl amide. Then, A THF solution (0.35 mL) of **4b** and chlorotrimethylsilane (0.75 mmol) was added to the reaction mixture and stirred at 0 ºC for 2 h. After quenched under air, the crude product was further purified by silica gel column chromatography (hexane**:**AcOEt = 99:1) to afford organic silicon compound (**7b**: 183.5 mg, 90%) as colorless oil. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.22 (s, 9H), 0.53 (m, *J* = 7.8 Hz, 6H), 0.86 (t, *J* = 7.8 Hz, 9H), 2.35 (s, 3H), 5.11 (dd, *J* = 16.1 Hz, 8.2 Hz, 1H), 7.15 (d, *J* = 7.9 Hz, 2H), 7.32 (d, *J* = 7.9 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): –4.0 (s), 4.8 (s), 6.7 (s), 21.4 (s), 72.1 (dd, *J* = 22.7 Hz, 30.6 Hz), 118.2 (m), 124.3 (m), 128.4 (s), 128.7 (s), 134.4 (s), 138.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –116.0 (dd, *J* = 282.1 Hz, 8.2 Hz, 1F), –123.0 (m, *J* = 282.1 Hz, 16.1 Hz, 7.6 Hz, 1F), –128.2 (d, *J* = 7.6 Hz, 2F). **HRMS (CI)**: *m/z* Calcd for $C_{19}H_{32}F_4OSi_2$ + H: 409.2006, Found: 409.2003.

3.8 References and Notes

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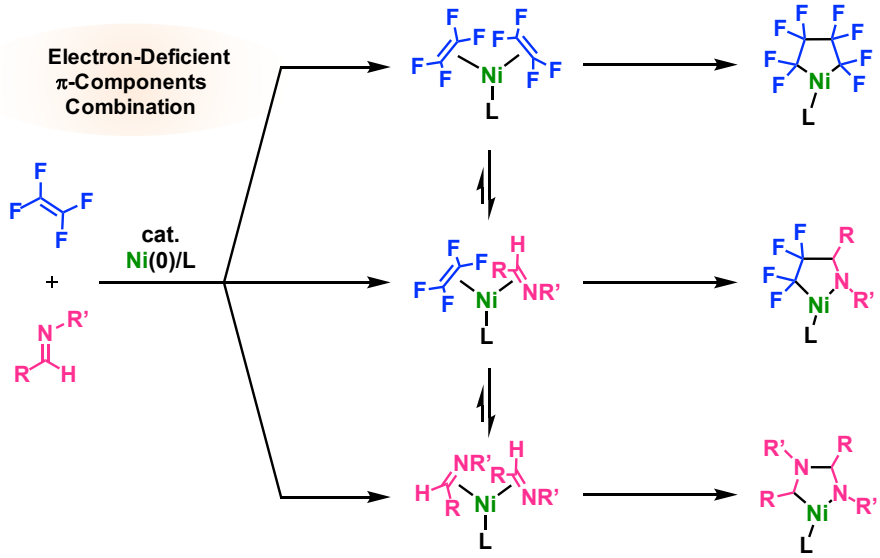
Chapter 4

Ni(0)-Catalyzed Three-Component Coupling Reaction of Tetrafluoroethylene and *N*-Sulfonyl-Substituted Imines with Silanes via Aza-Nickelacycles

4.1 Introduction

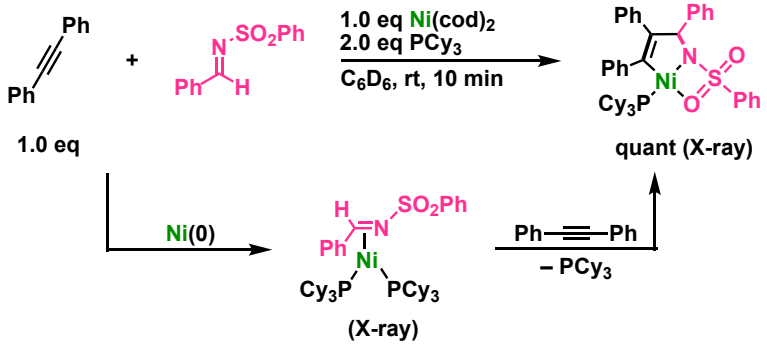
The oxa-nickelacyles generated from TFE and aldehydes served as key intermediates in the nickel-catalyzed three-component coupling reaction as shown in Chapter 3. Subsequently, we considered that the development of a catalytic system via aza-nickelacycle key intermediates generated from TFE and imines is a logical extension.[1,2] Since both TFE and imines are electron-deficient π-components, the oxidative cyclization of TFE and imines is a kinetically unfavorable reaction as in the case of aldehydes (Figure 4.1). In contrast to aldehydes, the simultaneous coordination and the oxidative cyclization of two molecules of imines are unlikely to proceed since these reactions have not been reported (Figure 4.1 bottom). Therefore, we estimated that the selective oxidative cyclization of TFE and imines could proceed via the formation of (η^2-TFE)(η^2-imine)Ni(0)L by the enhancement of the coordination ability of imines to Ni(0) (Figure 4.1 middle).

Figure 4.1. Selective Oxidative Cyclization between TFE and Imines.



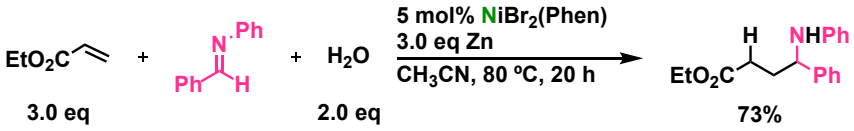
Therefore, we began our investigation using *N*-sulfonyl-substituted imines as model substrates for a Ni(0)-catalyzed three-component coupling reaction as we envisioned that they would: (i) enhance the coordination ability by back-donation from Ni(0) to the *N*-sulfonyl-substituted imines, and (ii) thermodynamically stabilize the generated aza-nickelacycle by coordination of the O atom of the *N*-sulfonyl group to the nickel center.[3] Our research group has reported the coordination of *N*-sulfonyl-substituted imines to Ni(0) and the oxidative cyclization of alkynes and *N*-sulfonyl-substituted imines to produce an aza-nickelacycle (Scheme 4.1).[3a] In addition, the generated aza-nickelacycle was thermodynamically stabilized by the intramolecular coordination of the O atom on *N*-sulfonyl groups to the nickel center.

Scheme 4.1. Acceleration of the Oxidative Cyclization by *N*-Sulfonyl Group.



A nickel-catalyzed three-component coupling reaction of alkenes and imines remains challenging. This is due to the difficulty of the simultaneous coordination of alkenes and imines to Ni(0), followed by the oxidative cyclization.[4] As one of such rare examples, a nickel-catalyzed three-component coupling reaction of activated conjugated alkenes and imines was reported by the group of Cheng (Scheme 4.2).[4a]

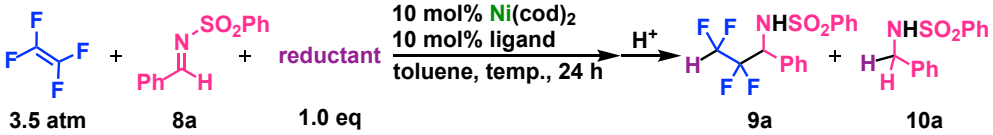
Scheme 4.2. Three-Component Coupling between Conjugated Alkenes and Imines.



4.2 Optimization of the Reaction Conditions

We optimized the reaction conditions for the Ni-catalyzed three-component coupling reaction of TFE, (*E*)-*N*-benzylidene benzenesulfonamide (**8a**), and a reductant (Table 4.1). Based on the optimal reaction conditions of our previous work in Chapter 3, a toluene solution of **8a** and Et_3SiH was exposed to TFE in presence of $Ni(cod)_2$ (10 mol%) and P^tBu_3 (10 mol%), followed by quenching with MeOH. However, *N*-(2,2,3,3-tetrafluoro-1-phenylpropyl)benzenesulfonamide (**9a**) was not obtained, even after 24 h at 100 °C (entry 1); instead, *N*-benzylbenzenesulfonamide (**10a**) was formed as an undesired product in 13% yield. Receiving this result, we studied the reaction with a variety of reductants. Employing BEt_3 and $ZnEt_2$ instead of Et_3SiH afforded neither **9a** nor **10a** (entries 2 and 3). The use of Ph_2SiH_2 furnished **9a** in 55% yield under concomitant generation of **10a** in 36% yield although the use of $PhSiH_3$ generated the less yield of **9a** (entries 4 and 5). Encouraged by this result, we subsequently examined the effect of the ligand with Ph_2SiH_2 to improve the yield of **9a**. Employing PCy_3 reduced the yield of **9a**, and IPr was ineffective for the catalytic reaction (entries 6 and 7). The yield of the reaction with PPh_3 (10 mol%) was comparable to that with P^tBu_3 although the oxidative cyclization of two molecules of TFE potentially proceeds as an undesired side reaction (entry 8). When the reaction was performed in the presence of 20 mol% of PPh_3, the yield of **9a** was decreased to 40% (entry 9). Control experiments showed that both $Ni(cod)_2$ and PPh_3 are necessary for this catalytic reaction (entries 10 and 11). Thus, further optimizations of the reaction conditions were carried out in the presence of 10 mol% of $Ni(cod)_2$ and PPh_3. Higher reaction temperatures (120 °C) and increased partial pressure of TFE (5.0 atm) slightly increased the yield of **9a** (entries 12 and 13). When the reaction was conducted under a TFE atmosphere (1.5 atm), **9a** was not formed (entry 14). These results revealed that the catalytic reaction proceeds favorably in the presence of an excess amount of TFE. Subsequently, the effect of silanes was studied. While $^tBu_2SiH_2$ was ineffective due to its steric bulkiness, Et_2SiH_2 generated **9a** in 80% yield and improved the **9a**/**10a** product ratio (entries 15 and 16). The use of P^tBu_3 instead of PPh_3 under the same reaction conditions in entry 16 afforded the less yield of **9a** (52%) (entry 17). Thus, we concluded the optimal reaction conditions as follows: $Ni(cod)_2$ (10 mol%) and PPh_3 (10 mol%) with Et_2SiH_2 in toluene at 120 ºC under a TFE atmosphere (5.0 atm).

Table 4.1. Optimization of the Reaction Conditions.



Entry	Ligand	Reductant	Temp. (°C)	Yield (%) 9a	10a
1	P^tBu_3	Et_3SiH	100	0	13
2[a]	P^tBu_3	BEt_3	100	0	0
3	P^tBu_3	$ZnEt_2$	100	0	0
4	P^tBu_3	Ph_2SiH_2	100	55	36
5	P^tBu_3	$PhSiH_3$	100	>1	55
6[b]	PCy_3	Ph_2SiH_2	100	6	54
7	IPr	Ph_2SiH_2	100	0	55
8[b]	PPh_3	Ph_2SiH_2	100	40	58
9	PPh_3	Ph_2SiH_2	100	51	29
10	none	Ph_2SiH_2	100	0	15
11[c]	PPh_3	Ph_2SiH_2	100	0	0
12	PPh_3	Ph_2SiH_2	120	53	55
13[d]	PPh_3	Ph_2SiH_2	120	57	42
14[e]	PPh_3	Ph_2SiH_2	120	0	99
15[d]	PPh_3	$^tBu_2SiH_2$	120	5	0
16[d]	PPh_3	Et_2SiH_2	120	80	6
17[d]	P^tBu_3	Et_2SiH_2	120	52	6

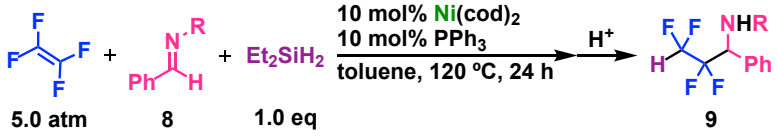
[a] The use of BEt_3 (1.0 M in THF). [b] 20 mol% of ligands. [c] Run without $Ni(cod)_2$. [d] 5.0 atm of TFE. [d] 1.5 atm of TFE.

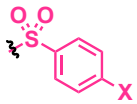
4.3 Effects of the *N*-Substituent of the Imine

The catalytic reactions were performed with a variety of *N*-substituted imines under the optimal reaction conditions to examine the effects of the *N*-substituent of the imines (Table 4.2). The yield of the corresponding target products was determined by ^{19}F NMR using α,α,α-trifluorotoluene as the internal standard. The use of (*E*)-*N*-benzylidene-4-methylbenzenesulfonamide (**8b**) instead of **8a** furnished the corresponding target compound (**9b**) in 70% yield (entry 2). Methoxy and trifluoromethyl-substituted imines **8c** and **8d** afforded lower yields of the desired products (**9c**: 51% and **9d**: 62%; entries 3 and 4). Although the reaction with (*E*)-*N*-benzylidene-2-methylbenzenesulfonamide (**8e**) afforded the target product (**9e**) in 76% yield after 24 h, 73% yield was obtained after 6 h (entry 5). The use of (*E*)-*N*-benzylidene-2,4,6-trimethylbenzenesulfonamide (**8f**), however, diminished the yield of the target compound **9f** in merely 38% yield (entry 6). Employing (*E*)-*N*-benzylidenemethanesulfonamide (**8g**) afforded the target compound **9g** in 67% yield within 6 h (entry 7). Neither (*E*)-*N*-benzylidenebenzenamine (**8h**) nor (*E*)-*tert*-butyl benzylidenecarbamate (**8i**) was effective for the catalytic reaction (entries 8 and 9). In addition, the reaction with *N*-diphenylphosphinic-substituted imine **8j** furnished no

target compound, even though it has been reported to accelerate the oxidative cyclization of alkynes and imines by thermodynamic stabilization of the resultant aza-nickelacycle (entry 10).[3c–d] These results revealed that the *N*-sulfonyl group on the imines is essential for the catalytic reaction.

Table 4.2. Effects of *N*-Substituent Group on Imines.



Entry		R		Yield (%)
1	8a:		X = H	68
2	8b:		X = Me	70
3	8c:		X = OMe	51
4	8d:		X = CF_3	62
5	8e:	SO_2(*o*-tol)		76 (73)[a]
6	8f:	SO_2(Mes)		38
7	8g:	SO_2Me		67[a]
8	8h:	Ph		0
9	8i:	Boc		0
10	8j:	$P(O)Ph_2$		0

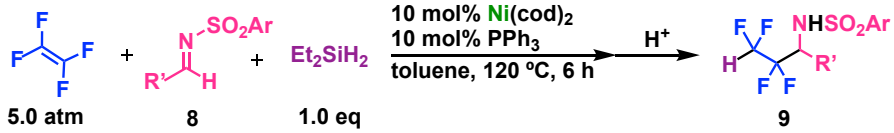
a Run for 6 h.

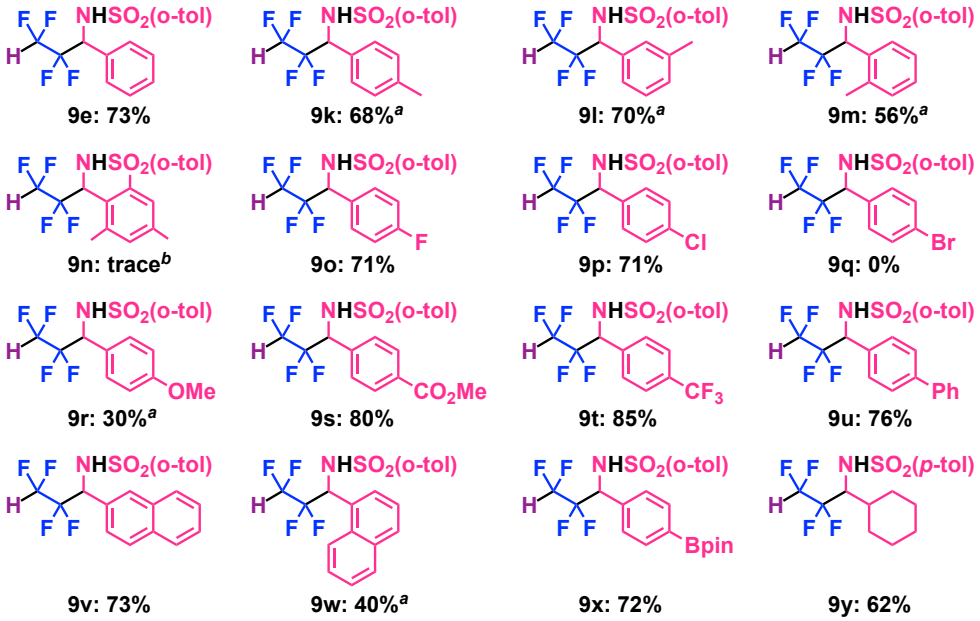
4.4 Substrate Scope

A variety of the target fluorine-containing amines were prepared by the nickel-catalyzed three-component coupling reaction with *N*-sufonyl-substituted imines under the optimal reaction condition (Table 4.3). The Ni(0)/PPh_3 system catalyzed the reaction of TFE, **8e**, and Et_2SiH_2 to afford **9e** in 73% isolated yield. The reactions with methyl-substituted imines (**8k**, **8l**, and **8m**) were completed within 12 h to furnish the corresponding target amines (**9k**, **9l**, and **9m**) in moderate to good yield; however, the reaction with trimethylphenyl imine (**8n**) furnished merely trace amounts of **9n**, which was detected by ^{19}F NMR analysis of the crude reaction mixture. Fluoro- (**8o**) and chloro-substituted imines (**8p**) generated the corresponding amines (**9o** and **9p**), although bromo-substituted imine **8q** could not be used as a substrate on account of the undesired oxidative addition of Ni(0) to a C–Br bond. The reaction of an imine with electron-donating group (**8r**) afforded the target compound (**9r**) in 30% yield, while the reactions of imines with electron-withdrawing groups, including ester, trifluoromethyl, and phenyl groups (**8s**, **8t**, and **8u**) generated the corresponding target compounds (**9s**, **9t**, and **9u**) in 80%, 85%, and 78% yield, respectively. Naphthyl imines (**8v** and **8w**) were tolerated to the catalytic reaction to form **9v** and

9w. The *p*-boronate-substituted amine **9x**, which can be further used as a coupling agent, was prepared from the catalytic reaction with a *p*-boronate-substituted imine (**8x**). Finally, the reaction with an aliphatic cyclic imine (**8y**) furnished the target compound **9y** in 62% yield.[5]

Table 4.3. Substrate Scope of Reaction with respect to Imines 9.



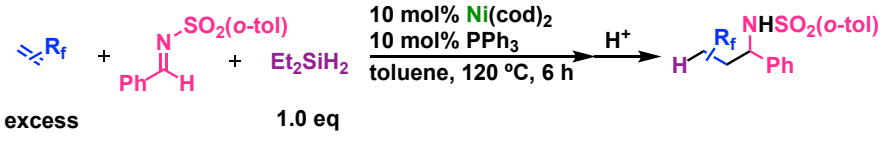


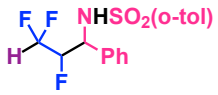
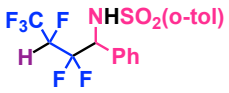
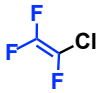
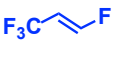
[a]Run for 12 h. [b] Estimated yield by ^{19}F NMR anaysis of the crude reaction mixture.

The scope and limitations of the catalytic reaction were examined using other industrially available fluorinated olefins (Table 4.4).[15] The reaction with trifluoroethylene afforded the target compound 2-methyl-*N*-(2,3,3-trifluoro-1-phenyl)propyl)benzenesulfonamide in 60% NMR yield (12:1 dr). However, the major product (the diastereomer) could not be isolated from the regioisomer, 2-methyl-*N*-(2,2,3-trifluoro-1-phenyl)propyl)benzenesulfonamide. The reaction with hexafluoropropylene in the presence of 20 mol% of the catalyst furnished *N*-(2,2,3,4,4,4-hexafluoro-1-phenylbutyl)-2-methylbenzenesulfonamide (the diastereomer) in 16% NMR yield. In addition, the major product was isolated from the diastereomer in 6% yield. The use of 1,1,2-trifluoro-2-chloroethylene did not afford the target compound due to the undesired oxidative addition of Ni(0) into a C-Cl bond. The use of other fluorinated olefins including difluoroethylene,

1,1,1,2-tetrafluoroprop-2-ene, and 1,3,3,3-tetrafluoropro-1-pene did not furnish the corresponding target compounds. This might be due to the difficulty of the simultaneous coordination and the oxidative cyclization since the coordination ability of these fluorinated olefins is weaker than that of *N*-sulfonyl-substituted imines.

Table 4.4. Substrate Scope of Reaction with respect to Fluorinated Olefins.



Fluorinated olefin	Target Compound	Yield (%)
2.0 atm 		60% (12:1 dr)[a]
5.0 atm 		16% (7:1 dr)[a,b]
inefficient    		

[a] Yield estimated by ^{19}F NMR analysis. [b] With 20 mol% of Ni(cod)$_2$ and PPh$_3$

4.5 Stoichiometric Reactions

In order to gain deeper insight into the reaction mechanism, stoichiometric reactions were conducted. When a toluene solution of Ni(cod)$_2$, PPh$_3$, and **8e** was exposed to TFE (1.5 atm, >6.8 eq.) at 60 °C for 7 h, a five-membered aza-nickelacycle dimer (***syn*-VII**) was generated in 76% isolated yield (Scheme 4.3a). In addition, monitoring the synthesis of ***syn*-VII** by NMR analysis revealed the formation of an η^2-*N*-sulfonyl-substituted imine nickel complex both in the absence and presence of excess amount of TFE.[3a] The molecular structure of ***syn*-VII** was unambiguously determined by single-crystal X-ray diffraction analysis. This analysis revealed that the O atom of the *N*-sulfonyl group occupies the vacant coordination site on the nickel center of another aza-nickelacycle monomer unit to stabilize the dimer complex in the solid state (Figure 4.2). The result contrasts with the findings of previous studies, where intramolecular coordination of the O atom of the *N*-sulfonyl group and the nickel center was observed.[3] When the reaction was conducted under higher pressure of TFE (5.0 atm, >18.7 eq.), the yield of ***syn*-VII** was decreased to 53%, and $(CF_2CF_2CF_2CF_2)Ni(PPh_3)_2$ was generated as a by-product in 12% yield.[6] The reaction of ***syn*-VII** with Et_2SiH_2 in C_6D_6 at 120 °C for 2 h, followed by quenching with MeOH, furnished

9e in 82% yield (Scheme 4.3b). These results revealed that either an aza-nickelacycle monomer or dimer generated via the oxidative cyclization of TFE and *N*-sulfonyl-substituted imines is the key intermediate in the catalytic reaction.

Scheme 4.3. Stoichiometric Reactions.

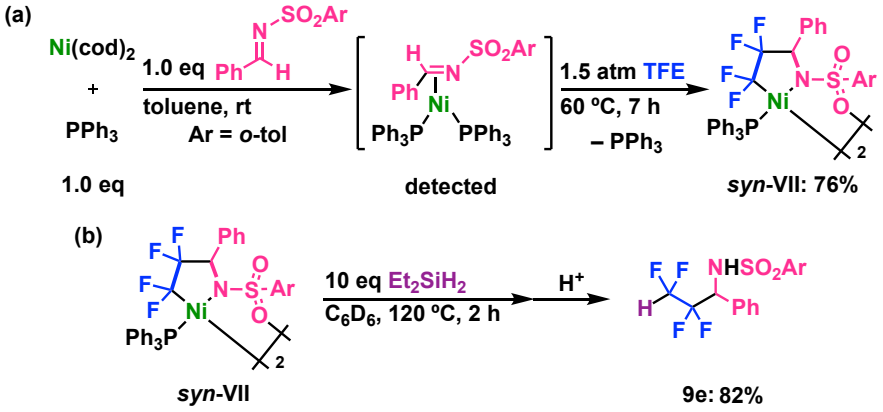
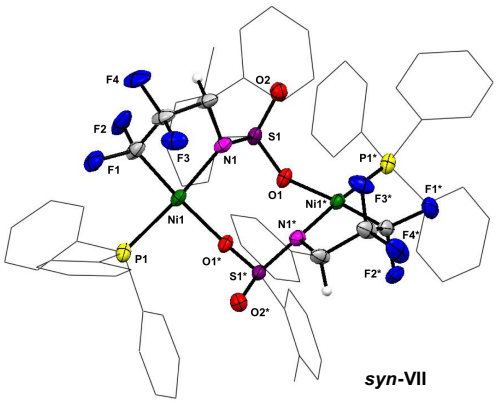
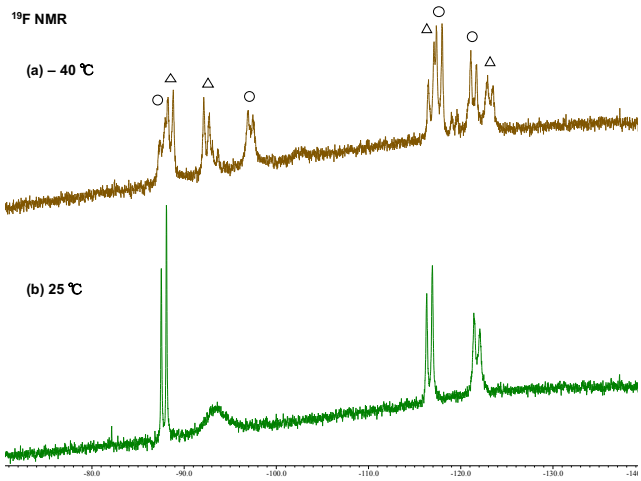


Figure 4.2. ORTEP representation of *syn*-VII with thermal ellipsoids at the 30% probability (except for the organic substituents including the *o*-tolyl and phenyl groups); selected hydrogen atoms have been omitted for clarity.



Subsequently, variable-temperature NMR experiments were conducted (Figure 4.3). A crystal of ***syn*-VII** was dissolved in toluene-d_8 at –40 °C and examined by ^{19}F NMR spectroscopy at that temperature. Sharp resonances corresponding to two different complexes were observed although only ***syn*-VII** was identified in the crystal structure (Figure 4.3a). When the toluene-d_8 solution was heated to room temperature, the sharp resonances coalesced into broader signals (Figure 4.3b). These variable-temperature NMR experiments suggest that a mixture of several complexes (including ***syn*-VII**) exists in equilibrium in solution at room temperature.

Figure 4.3. Variable-temperature NMR experiments of *syn*-VII in toluene-d_8. ^{19}F NMR spectra at (a) –40 °C and (b) room temperature.



The reaction of **8h** instead of **8e** with $Ni(cod)_2$ and PPh_3 under an atmosphere of TFE (1.5 atm) afforded octafluoronickelacyclopentane (**VIII**), which was generated via the oxidative cyclization of two molecules of TFE, in 15% yield (Scheme 4.4). The molecular structure of **VIII**, which was confirmed by single-crystal X-ray diffraction analysis, exhibits a distorted square-planar geometry in the solid state (Figure 4.4). The expected aza-nickelacycles generated from TFE and **8h** were not obtained, while a η^2-*N*-phenyl imine nickel complex was observed by NMR analysis in C_6D_6 before exposure to TFE (the bottom of Scheme 4.4). Moreover, the reaction of **VIII** with Et_2SiH_2 was performed in order to consider the possibility of retro-oxidative cyclization. However, the target product (**9h**) was not obtained, not even at 120 °C. These results revealed that the *N*-sulfonyl groups on the imines are crucial to accelerate the oxidative cyclization and generate the thermodynamically stabilized aza-nickelacycle intermediates.

Scheme 4.4. Stoichiometric Reactions.

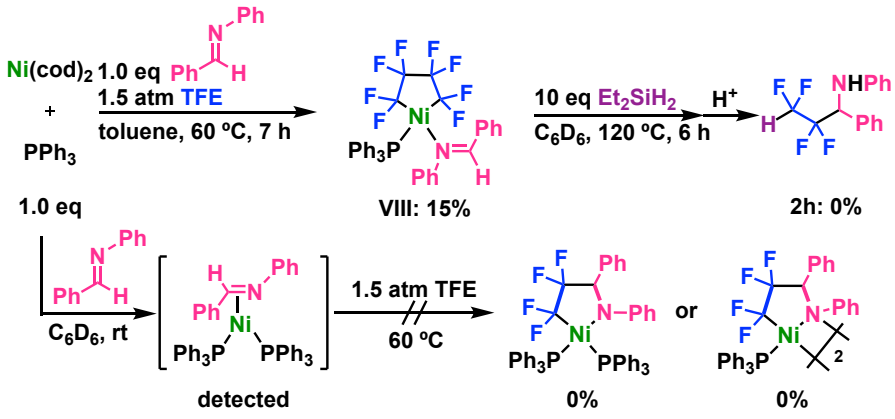
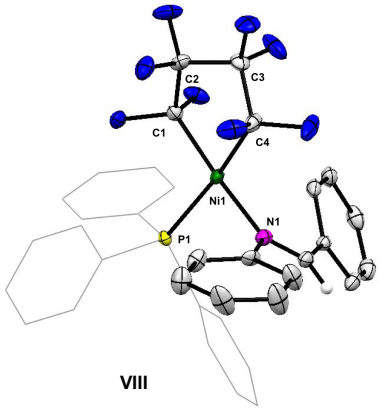


Figure 4.4. ORTEP representation of VIII with thermal ellipsoids at 30% probability (except for Ph groups of the PPh_3); selected H atoms have been omitted for clarity.

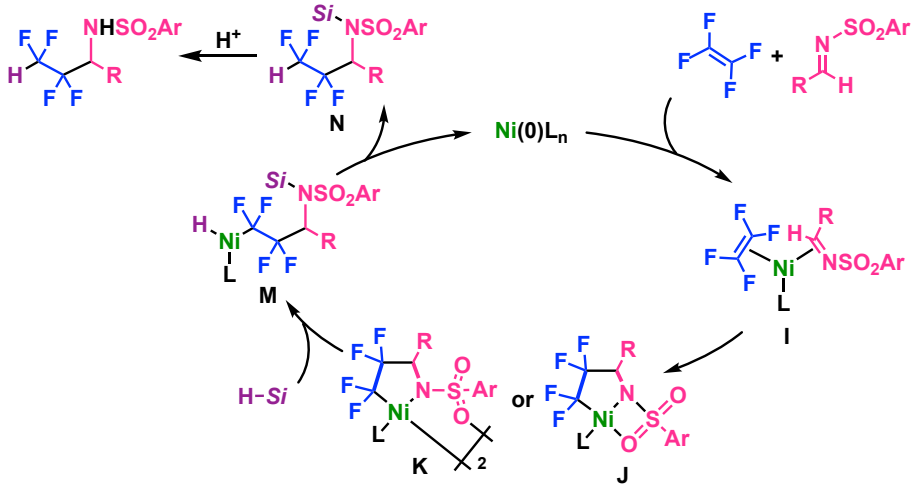


VIII

4.6 Plausible Reaction Mechanism

Based on these results, a plausible reaction mechanism for the present nickel-catalyzed three-component coupling reaction is depicted in Scheme 4.5. First, A simultaneous coordination of TFE and the *N*-sulfonyl-substituted imine with Ni(0) gives η^2:η^2 nickel complex **I**. Afterward, an oxidative cyclization produces an aza-nickelacycle monomer (**J**) and/or dimer (***syn*-K** or ***anti*-K**) as key intermediates, which would be stabilized by coordination of the *N*-sulfonyl group to the nickel center. Then, transmetallation of the silane with **J**, ***syn*-K**, or ***anti*-K** affords nickel hydride **M**. A reductive elimination on **M** generates **N** under concomitant regeneration of the Ni(0) species. Finally, **N** is protonated during the workup to give the target product. All of our attempts to isolate **N** have remained unsuccessful.

Scheme 4.5. Plausible Reaction Mechanism.



4.7 Application

In order to demonstrate the utility of this catalytic reaction, we studied the reactivity of the obtained product **9k** (Scheme 4.6). A THF solution of **9k** and lithium diisopropyl amide (LDA) as a Lewis base was stirred for 2 h at –20 ºC, followed by quenching with MeOH, to afford trifluoro allylic amine **11k** in 82% isolated yield. Since trifluorovinyl compounds are active toward radical polymerization reaction, this product might be used as a co-monomer for the production of fluorine-containing polymer. In addition, the adhesive properties[7] and solubility[8] of fluorine-containing polymers might be tuned on account of the amine group. Moreover, this product may serve as a versatile intermediate for the synthesis of various fluorinated compounds, since the trifluorovinyl moiety is active toward nucleophiles.[9] This transformation exemplified the synthetic utility of the present catalytic system. In addition, all attempts for the deprotection of the sulfonyl group-substituted reaction product to give *N*-protonated amine were unsuccessful so far.[10]

Scheme 4.6. Utility of Fluorine-containing Amines 9k.

9k **11k: 82%**

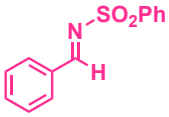
4.8 Conclusion

In Chapter 4, the Ni(0)/PPh_3-catalyzed three-component coupling reaction of TFE, *N*-sulfonyl-substituted imines, and Et_2SiH_2 was demonstrated to afford a variety of fluorine-containing amines. The key intermediate of the catalytic reaction is an aza-nickelacycle generated from TFE and *N*-sulfonyl-substituted imine, which was confirmed by the stoichiometric reactions and single-crystal X-ray diffraction analysis. The *N*-sulfonyl group on the imines is crucial for the present catalytic reaction since it can enhance the coordination ability of the imines to Ni(0) and stabilize the resulting aza-nickelacycle intermediates. The obtained products can be deprotonated by Lewis base and transformed into trifluoro allylic amines, which can be further used as a co-monomer and a versatile intermediate.

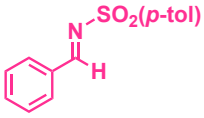
4.9 Experimental Section

General procedure for the preparation of Imines: Aryl *N*-sulfonyl-substituted imines were prepared by the known procedures.[11] A $CHCl_3$ solution (35 mL) of aldehydes (a given amount), a given

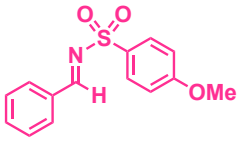
sulfonamides (10 mmol), and 4Å molecular sieves (1 g/mmol) was stirred at 60 ºC for 24 h in the presence of pyrrolidine (1.0 mmol). The reaction mixture was filtered, and the crude product was purified by silica gel column chromatography (elute: hexane:AcOEt = 8:2) followed by recrystallization from toluene and hexane.



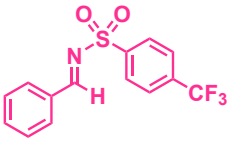
(*E*)-*N*-Benzylidene benzenesulfonamide (**8a**) is commercially available.



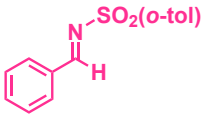
(*E*)-*N*-Benzylidene-4-methylbenzenesulfonamide (8b): Prepared from benzaldehyde (12 mmol) and 4-methylbenzenesulfonamide. White solid; Yield: 68% (1.8 g); The chemical shifts were consistent with those reported in the literature.[12]



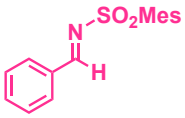
(*E*)-*N*-Benzylidene-4-methoxybenzenesulfonamide (8c): Prepared from benzaldehyde (12 mmol) and 4-methoxybenzenesulfonamide. White solid; Yield: 60% (1.7 g); The chemical shifts were consistent with those reported in the literature.[13]



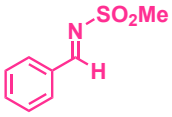
(*E*)-*N*-Benzylidene-4-trifluoromethylbenzenesulfonamide (8d): Prepared from benzaldehyde (12 mmol) and 4-trifluoromethylbenzenesulfonamide. White solid; Yield: 64% (2.0 g); The chemical shifts were consistent with those reported in the literature.[14]



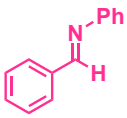
(*E*)-*N*-Benzylidene-2-methylbenzenesulfonamide (8e): Prepared from benzaldehyde (12 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 67% (2.3 g); The chemical shifts were consistent with those reported in the literature.[13]



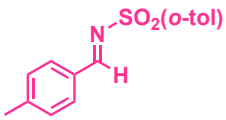
(*E*)-*N*-Benzylidene-2,4,6-trimethylbenzenesulfonamide (8f): Prepared from benzaldehyde (12 mmol) and 2,4,6-trimethylbenzenesulfonamide. White solid; Yield: 91% (2.6 g); The chemical shifts were consistent with those reported in the literature.[15]



(*E*)-*N*-benzylidenemethanesulfonamide (8g): This reaction was conducted with benzaldehyde (7.5 mmol), methanesulfonamide (5.0 mmol), and 4Å molecular sieves (1 g/mmol) in a $CHCl_3$ solution (35 mL) in the presence of pyrrolidine (1.0 mmol) at 60 ºC for 12 h. The reaction mixture was filtered, and the crude product was washed with hexane. White solid; Yield: 42% (382.7 mg); The chemical shifts were consistent with those reported in the literature.[16]

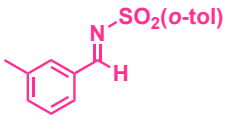


(*E*)-*N*,1-Diphenylmethanimine (**8h**) is commercially available.

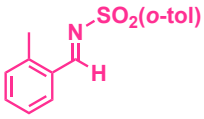


(*E*)-2-Methyl-*N*-(4-methylbenzylidene)benzenesulfonamide (8k): Prepared from 4-methylbenzaldehyde (12 mmol) and 2-methylbenzenesulfonamide by Procedure A. White solid;

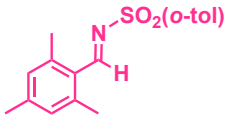
Yield: 95% (2.6 g); The chemical shifts were consistent with those reported in the literature.[17]



(*E*)-2-Methyl-*N*-(3-methylbenzylidene)benzenesulfonamide (8l): Prepared from 3-methylbenzaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 86% (2.4 g); mp: 74.7–74.9 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.40 (s, 3H), 2.74 (s, 3H), 7.32–7.45 (4H), 7.50 (dd, *J* = 7.5 Hz, 7.3 Hz, 1H), 7.72 (d, *J* = 8.1 Hz, 1H), 7.76 (s, 1H), 8.10 (d, *J* = 7.6 Hz, 1H), 9.06 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 21.3 (s), 126.5 (s), 129.1 (s), 129.3 (s), 129.4 (s), 131.6 (s), 132.5 (s), 132.6 (s), 133.8 (s), 136.1 (s), 136.7 (s), 139.0 (s), 139.3 (s), 171.1 (s). **HRMS (EI)**: *m/z* Calcd for $C_{15}H_{15}NO_2S$: 273.0823, Found: 273.0826.

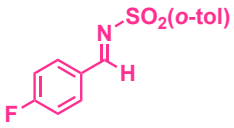


(*E*)-2-Methyl-*N*-(2-methylbenzylidene)benzenesulfonamide (8m): Prepared from 1-methylbenzaldehyde (11 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 77% (2.1 g); mp: 112.1–112.5 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.62 (s, 3H), 2.77 (s, 3H), 7.28–7.38 (4H), 7.49 (dd, *J* = 7.6 Hz, 7.4 Hz, 1H), 7.50 (dd, *J* = 7.7 Hz, 7.4 Hz, 1H), 8.00 (d, *J* = 7.7 Hz, 1H), 8.10 (d, *J* = 7.6 Hz, 1H), 9.40 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 19.9 (s), 20.7 (s), 126.4 (s), 126.7 (s), 129.2 (s), 130.5 (s), 131.0 (s), 131.7 (s), 132.5 (s), 133.7 (s), 134.7 (s), 136.7 (s), 138.9 (s), 142.3 (s), 169.4 (s). **HRMS (EI)**: *m/z* Calcd for $C_{15}H_{15}NO_2S$: 273.0823, Found: 273.0826.

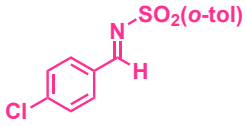


(*E*)-2-Methyl-*N*-(2,4,6-trimethylbenzylidene)benzenesulfonamide (8n): Prepared from 2,4,6-trimethylbenzaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 39% (1.2 g); mp: 107.4–107.8 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.32 (s, 3H), 2.55 (s, 6H), 2.77 (s, 3H), 6.93 (s, 2H), 7.32 (d, *J* = 7.5 Hz, 1H), 7.33 (dd, *J* = 7.8 Hz, 7.2 Hz, 1H), 7.49 (dd, *J* = 7.5 Hz, 7.2 Hz, 1H), 8.08 (d, *J* = 7.8 Hz, 1H), 9.53 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.6 (d, *J* = 2.2 Hz), 21.7 (d, *J* = 1.5 Hz), 22.0 (d, *J* = 2.2 Hz), 126.2 (s), 126.3 (s), 129.1 (s), 130.8 (s), 132.5 (s),

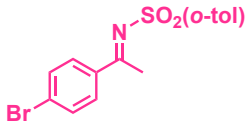
133.5 (s), 137.2 (s), 138.8 (s), 143.1 (s), 145.0 (s), 169.5 (d, J = 1.5 Hz). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{19}NO_2S$: 323.1136, Found: 323.1141.



(*E*)-2-Methyl-*N*-(4-fluorobenzylidene)benzenesulfonamide (8o): Prepared from 4-fluorobenzaldehyde (11 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 73% (2.0 g); mp: 116.4–116.6 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.74 (s, 3H), 7.19 (d, J = 8.2 Hz, 8.1 Hz, 2H), 7.35 (d, J = 7.4 Hz, 1H), 7.36 (dd, J = 7.5 Hz, 7.3 Hz, 1H), 7.51 (ddd, J = 7.4 Hz, 7.3 Hz, 1.0 Hz, 1H), 7.97 (dd, J = 8.2 Hz, 5.6 Hz, 2H), 8.09 (dd, J = 7.5 Hz, 1.0 Hz, 1H), 9.06 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 116.7 (s), 117.0 (s), 126.5 (s), 128.9 (d, J = 2.9 Hz), 129.4 (s), 132.6 (s), 133.8 (s), 133.9 (s), 134.0 (s), 136.5 (s), 139.0 (s), 167.0 (d, J = 261.9 Hz), 169.2 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –103.6 (m, J = 8.1 Hz, 5.6 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{14}H_{12}FNO_2S$: 277.0573, Found: 277.0575.

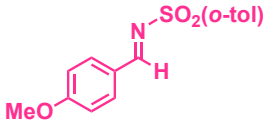


(*E*)-2-Methyl-*N*-(4-chlorobenzylidene)benzenesulfonamide (8p): Prepared from 4-chlorobenzaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 29% (0.9 g); The chemical shifts were consistent with those reported in the literature.[17]

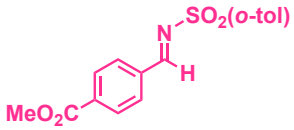


(*E*)-2-Methyl-*N*-(4-bromobenzylidene)benzenesulfonamide (8q): Prepared from 4-bromobenzaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 68% (2.3 g); mp: 141.2–141.6 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.74 (s, 3H), 7.35 (d, J = 7.7 Hz, 1H), 7.36 (dd, J = 7.8 Hz, 7.3 Hz, 1H), 7.51 (ddd, J = 7.7 Hz, 7.3 Hz, 1.3 Hz, 1H), 7.64 (d, J = 8.5 Hz, 2H), 7.79 (d, J = 8.5 Hz, 2H), 8.09 (dd, J = 7.8 Hz, 1.3 Hz, 1H), 9.05 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 126.5 (s), 129.5 (s), 130.5 (s), 131.4 (s), 132.5 (s), 132.6 (s), 132.8 (s), 133.9 (s), 136.4 (s), 139.0 (s), 169.5 (s). **HRMS (EI)**: *m/z* Calcd for $C_{14}H_{12}BrNO_2S$: 336.9772, Found:

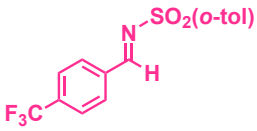
336.9777.



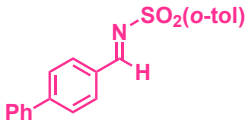
(*E*)-2-Methyl-*N*-(4-methoxybenzylidene)benzenesulfonamide (8r): Prepared from 4-methoxybenzaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 92% (2.7 g); The chemical shifts were consistent with those reported in the literature.[17]



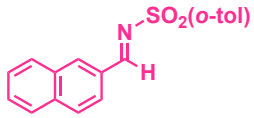
Methyl (*E*)-2-((tosylimino)methyl)benzoate (8s): Prepared from methyl 4-formylbenzoate (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 65% (2.1 g); mp: 165.2–165.5 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.76 (s, 3H), 3.95 (s, 3H), 7.35 (d, J = 7.5 Hz, 1H), 7.37 (dd, J = 7.9 Hz, 7.3 Hz, 1H), 7.52 (ddd, J = 7.5 Hz, 7.3 Hz, 1.0 Hz, 1H), 8.00 (d, J = 8.5 Hz, 2H), 8.09 (dd, J = 7.9 Hz, 1.0 Hz, 1H), 8.14 (d, J = 8.5 Hz, 2H), 9.14 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 52.7 (s), 126.5 (s), 129.5 (s), 130.2 (s), 131.1 (s), 132.6 (s), 134.0 (s), 135.5 (s), 136.0 (s), 136.1 (s), 139.1 (s), 165.9 (s), 169.6 (s). **HRMS (EI)**: *m/z* Calcd for $C_{16}H_{15}NO_4S$: 317.07222, Found: 317.0724.



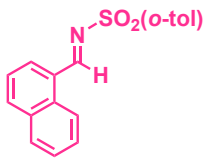
(*E*)-2-Methyl-*N*-(4-trifluoromethylbenzylidene)benzenesulfonamide (8t): Prepared from 4-trifluorobenzaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 63% (2.1 g); mp: 132.7–133.0 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.65 (s, 3H), 7.26 (d, J = 7.4 Hz, 1H), 7.28 (d, J = 8.2 Hz, 7.6 Hz, 1H), 7.44 (dd, J = 7.6 Hz, 7.4 Hz, 1H), 7.66 (d, J = 7.1 Hz, 2H), 7.96 (d, J = 7.1 Hz, 2H), 8.00 (d, J = 8.2 Hz, 1H), 9.05 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 123.4 (q, J = 272.7 Hz), 126.3 (q, J = 4.0 Hz), 126.6 (s), 129.6 (s), 131.5 (s), 132.7 (s), 134.1(s), 135.7 (d, J = 52.9 Hz), 136.0 (d, J = 33.1 Hz), 139.2 (s), 169.1 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –66.0 (s, 3F). **HRMS (EI)**: *m/z* Calcd for $C_{15}H_{12}F_3NO_2S$: 327.0541, Found: 327.0536.



(*E*)-2-Methyl-*N*-(4-phenylbenzylidene)benzenesulfonamide (8u): Prepared from 4-phenylbenzaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 61% (2.0 g); mp: 113.5–113.8 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.77 (s, 3H), 7.3–7.6 (6H), 7.63 (d, *J* = 7.3 Hz, 2H), 7.73 (d, *J* = 8.2 Hz, 2H), 8.01 (d, *J* = 8.2 Hz, 2H), 8.12 (d, *J* = 7.8 Hz, 1H), 9.13 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 126.5 (s), 127.4 (s), 127.9 (s), 128.8 (s), 129.2 (s), 129.4 (s), 131.3(s), 132.0 (s), 132.6 (s), 133.8 (s), 136.7 (s), 139.0 (s), 139.5 (s), 147.9 (s), 170.3 (s). **HRMS (EI)**: *m/z* Calcd for $C_{20}H_{17}NO_2S$: 335.0980, Found: 335.0980.

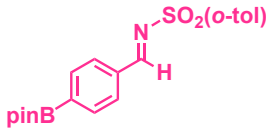


(*E*)-2-Methyl-*N*-(4-naphthalen-2-ylmethylene)benzenesulfonamide (8v): Prepared from 2-naphtaldehyde (10 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 72% (2.2 g); mp: 137.7–138.1 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.79 (s, 3H), 7.36 (d, *J* = 7.2 Hz, 1H), 7.37 (dd, *J* = 8.2 Hz, 7.8 Hz, 1H), 7.51 (dd, *J* = 7.7 Hz, 7.2 Hz, 1H), 7.58 (dd, *J* = 8.4 Hz, 7.2 Hz, 1H), 7.64 (dd, *J* = 7.8 Hz, 7.2 Hz, 1.3 Hz, 1H), 7.89 (d, *J* = 7.7 Hz, 1H), 7.88 (d, *J* = 8.4 Hz, 1H), 7.96 (d, *J* = 8.1 Hz, 1H), 8.04 (dd, *J* = 8.2 Hz, 1.3 Hz, 1H), 8.14 (d, *J* = 8.1 Hz, 1H), 8.33 (s, 1H), 9.24 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 124.1 (s), 126.5 (s), 127.4 (s), 128.2 (s), 129.4 (s), 129.4 (s), 129.7 (s), 130.3 (s), 132.6 (s), 132.8 (s), 133.8 (s), 136.4 (s), 136.7 (s), 136.8 (s), 139.0 (s), 170.7 (s). **HRMS (EI)**: *m/z* Calcd for $C_{18}H_{15}NO_2S$: 309.0823, Found: 309.0825.

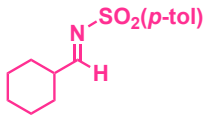


(*E*)-2-Methyl-*N*-(4-naphthalen-1-ylmethylene)benzenesulfonamide (8w): Prepared from 1-naphtaldehyde (15 mmol) and 2-methylbenzenesulfonamide. White solid; Yield: 55% (1.7 g); mp: 123.0–123.2 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.82 (s, 3H), 7.36 (d, *J* = 7.6 Hz, 1H), 7.37 (dd, *J* = 8.4 Hz, 7.8 Hz, 1H), 7.51 (dd, *J* = 7.8 Hz, 7.6 Hz, 1.3 Hz, 1H), 7.57–7.63 (2H), 7.69 (m, *J* = 7.0 Hz, 1.5 Hz, 1H), 7.94 (d, *J* = 7.6 Hz, 1H), 8.12 (d, *J* = 8.5 Hz, 1H), 8.14–8.18 (2H), 9.01 (d, *J*

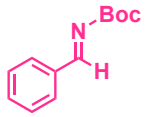
= 8.4 Hz, 1H), 9.67 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 124.3 (s), 125.3 (s), 126.5 (s), 127.1 (s), 127.8 (s), 129.1 (s), 129.3 (s), 129.4 (s), 131.9 (s), 132.6 (s), 133.7 (s), 134.0 (s), 135.5 (s), 136.4 (s), 136.9 (s), 138.9 (s), 170.5 (s). **HRMS (EI)**: *m/z* Calcd for $C_{18}H_{15}NO_2S$: 309.0823, Found: 309.0823.



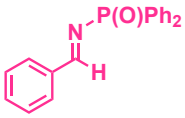
(*E*)-2-Methyl-*N*-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzylidene)benzenesulfonamide (1x): Prepared from 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzaldehyde (4.5 mmol) and 2-methylbenzenesulfonamide (4.5 mmol). White solid; Yield: 82% (1.4 g); mp: 160.2–160.3 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 1.23 (s, 12H), 2.62 (s, 3H), 7.22 (d, *J* = 7.2 Hz, 1H), 7.23 (d, *J* = 7.9 Hz, 7.6 Hz, 1H), 7.39 (dd, *J* = 7.6 Hz, 7.2 Hz, 1H), 7.79 (br, 4H), 7.98 (d, *J* = 7.9 Hz, 1H), 8.98 (s, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.8 (s), 25.0 (s), 84.5 (s), 126.5 (s), 129.5 (s), 130.4 (s), 132.6 (s), 133.8 (s), 134.5 (s), 135.4 (s), 136.5 (s), 139.0 (s), 170.8 (s). **HRMS (EI)**: *m/z* Calcd for $C_{20}H_{24}BNO_4S$: 385.1519, Found: 385.1515.



Experimental procedure for the preparation of (*E*)-*N*-(Cyclohexylmethylene)-4-methylbenzenesulfonamide (1y):[18] A H_2O solution (30 mL) of cyclohexanecarboaldehyde (20 mmol), 4-methylbenzenesulfonamide (20 mmol), and sodium 4-methylbenzenesulfinate (20 mmol) was stirred at room temperature for 24 h in the presence of HCOOH (30 mL). The reaction mixture was filtered, and the crude product was washed with H_2O and pentane, followed by extraction by CH_2Cl_2 and sat. $NaHCO_3$ aq. Then, the organic layer was dried by anhydrous $MgSO_4$ and concentrated under reduced pressure. White solid; Yield: 66% (3.5 g): The chemical shifts were consistent with those reported in the literature.[19]



Experimental procedure for the preparation of *N-tert*-Butyl-benzylidenecarbamate (1i):[20] A methanol (30 mL) and water (60 mL) solution of benzaldehydes (40 mmol), *tert*-butyl carbamate (20 mmol), benzenesulfinic acid sodium salt (50 mmol), and formic acid (40 mmol) was stirred at room temperature for 24 h. The reaction mixture was filtered, and the crude product washed with Et_2O. Then, a THF solution (40 mL) of the obtained product (10 mmol), potassium carbonate (60 mmol), and sodium sulfate (70 mmol) was refluxed for 18 h. The reaction mixture was filtered and concentrated to give the target imine. White solid; Yield: 80% (2.1 g); The spectral data of the product are reported in the literature.[19]



Experimental procedure for the preparation of *N*-(4-Methoxybenzylidene)-*P,P*-diphenylphosphinic amide (1j):[21] A $CHCl_3$ solution (14 mL) of benzaldehydes (4.8 mmol), *P,P*-diphenylphosphinic amide (4 mmol), and 4Å molecular sieves (1 g/mmol) was stirred at 60 ºC for 24 h in the presence of pyrrolidine (0.4 mmol). The reaction mixture was filtered, and the crude product was purified by silica gel column chromatography (elute: hexane:AcOEt = 8:2), followed by recrystallization from toluene and hexane. White solid; Yield: 81% (985.9 mg); The spectral data of the product are reported in the literature.[20]

General procedure for the optimization of the reaction conditions: All catalytic reactions were conducted with a pressure-tight NMR tube (Wilmad-LabGlass, 524-PV-7). A toluene solution (0.5 mL) of $Ni(cod)_2$ (2.8 mg, 0.010 mmol), a ligand, **8a** (0.10 mmol), and reductant (0.10 mmol) was exposed to TFE (either 3.5 atm, >0.30 mmol or 5.0 atm. >0.40 mmol). The reaction mixture was heated to a given temperature for 24 h, and quenched with MeOH. The yield of **9a** and **10a** were determined by gas chromatography using *n*-hexadecane as the internal standard.

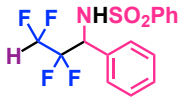
General procedure for the evaluation of effect of the *N*-sulfonyl groups on the imines: All catalytic reactions were conducted with a pressure-tight NMR tube (Wilmad-LabGlass, 524-PV-7). A toluene solution (0.5 mL) of $Ni(cod)_2$ (2.8 mg, 0.010 mmol), PPh_3 (2.6 mg, 0.010 mmol), a given imine (**8**: 0.10 mmol), and Et_2SiH_2 (8.8 mg, 0.10 mmol) was exposed to TFE (5.0 atm. >0.40 mmol). The reaction mixture was heated to 120 ºC for 24 h, and quenched with MeOH. The yield of the corresponding target compounds was determined by ^{19}F NMR analysis using α,α,α-trifluorotoluene

as the internal standard.

General procedure A for the substrate scope with the respect to imines: A toluene solution (3.0 mL) of $Ni(cod)_2$ (13.8 mg, 0.05 mmol), PPh_3 (13.1 mg, 0.05 mmol), a given imine (**8**: 0.50 mmol), and Et_2SiH_2 (44.1 mg, 0.50 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). Then, TFE (5.0 atm) was charged into the autoclave reactor. The reaction mixture was stirred at 120 ºC for a given time. The unreacted TFE was purged from the autoclave reactor. (caution: The reaction mixture must be handle in a well-ventilated fume hood.) The reaction mixture was quenched with MeOH and filtrated to remove insoluble residue. All volatiles were removed under reduced pressure, and the crude product was purified by silica gel column chromatography, giving the title compound **9**.

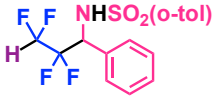
General procedure B for the substrate scope with the respect to imines: A toluene solution (3.0 mL) of $Ni(cod)_2$ (13.8 mg, 0.05 mmol), PPh_3 (13.1 mg, 0.05 mmol), a given imine (**8**: 0.50 mmol), and Et_2SiH_2 (44.1 mg, 0.50 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). Then, TFE (5.0 atm) was charged into the autoclave reactor. The reaction mixture was stirred at 120 ºC for a given time. The unreacted TFE was purged from the autoclave reactor. (caution: The reaction mixture must be handle in a well-ventilated fume hood.) The reaction mixture was quenched with MeOH and filtrated to remove insoluble residue. All volatiles were removed under reduced pressure, and the crude product was purified by silica gel column chromatography and high performance liquid chromatography (HPLC), giving the title compound **9**.

General procedure C for the substrate scope with the respect to imines: A toluene solution (0.5 mL) of $Ni(cod)_2$ (2.8 mg, 0.010 mmol), PPh_3 (2.6 mg, 0.010 mmol), a given imine (**8**: 0.10 mmol), Et_2SiH_2 (0.10 mmol) was transferred into a pressure-tight NMR tube. Then, TFE (5.0 atm, >0.40 mmol) was charged into the reaction tube. The reaction mixture was heated to 120 ºC for 6 h. The reaction mixture was quenched with MeOH, and C_6D_6 and α,α,α-trifluorotoluene as the internal standard were added to estimate the yield of the desired product **9** by ^{19}F NMR analysis.

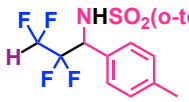


***N*-(2,2,3,3-tetrafluoro-1-phenylpropyl)benzenesulfonamide (9a):** mp: 125.2–125.8 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.29 (s, 3H), 2.43 (s, 3H), 4.65 (m, J = 12.1 Hz, 9.5 Hz, 1H), 5.32 (d, J = 9.5 Hz, 1H), 5.76 (dddd, J = 53.2 Hz, 52.3 Hz, 4.9 Hz, 1H), 6.95 (d, J = 7.8 Hz, 2H), 7.02 (d, J =

7.8 Hz, 2H), 7.12 (d, J = 7.7 Hz, 1H), 7.23 (dd, J = 8.0 Hz, 7.4 Hz, 1H), 7.38 (dd, J = 7.7 Hz, 7.4 Hz, 1H), 7.87 (d, J = 8.0 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 21.2 (s), 57.5 (dd, J = 24.5 Hz, 23.6 Hz), 108.9 (dddd, J = 251.6 Hz, 31.0 Hz), 115.2 (dddd, J = 254.9 Hz, 24.5 Hz), 126.3 (s), 127.9 (s), 129.0 (s), 129.7 (s), 132.5 (s), 133.2 (s), 137.2 (s), 137.5 (s), 139.6 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.4 (br, J = 266.4 Hz, 1F), –129.2 (br, J = 266.4 Hz, 1F), –140.4 (dddd, J = 302.8 Hz, 52.3 Hz, 1F), –142.7 (dddd, J = 302.8 Hz, 53.2 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{17}F_4NO_2S$: 375.0598, Found: 347.0607.

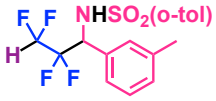


2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-phenyl)propyl)benzenesulfonamide (9e): The general procedure A was followed with **8e** (129.7 mg, 0.50 mmol), and the reaction mixture was stirred for 6 h. Purification by silica gel column chromatography (elute: CH_2Cl_2) gave **9e** (131.9 mg, 73%) as white solid. mp: 125.0–125.6 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.41 (s, 3H), 4.69 (m, J = 12.8 Hz, 9.3 Hz, 1H), 5.33 (d, J = 9.3 Hz, 1H), 5.79 (dddd, J = 53.2 Hz, 52.7 Hz, 4.7 Hz, 1H), 7.05 (d, J = 7.1 Hz, 2H), 7.09 (d, J = 7.3 Hz, 1H), 7.22 (dd, J = 7.4 Hz, 7.1 Hz, 2H), 7.24 (dd, J = 7.9 Hz, 7.7 Hz, 1H), 7.28 (t, J = 7.4 Hz, 1H), 7.37 (dd, J = 7.7 Hz, 7.3 Hz, 1H), 7.87 (d, J = 7.9 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 57.6 (dd, J = 24.0 Hz, 23.9 Hz), 108.8 (dddd, J = 251.3 Hz, 32.7 Hz), 115.1 (dddd, J = 256.3 Hz, 255.9 Hz, 26.2 Hz, 25.6 Hz), 126.3 (s), 128.0 (s), 129.0 (s), 129.5 (s), 129.7 (s), 131.8 (s), 132.6 (s), 133.3 (s), 137.1 (s), 137.3 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.3 (m, J = 267.0 Hz, 12.8 Hz, 7.6 Hz, 5.2 Hz, 1F), –129.0 (m, J = 267.0 Hz, 12.8 Hz, 7.6 Hz, 7.2 Hz, 1F), –140.0 (dddd, J = 302.1 Hz, 52.7 Hz, 7.2 Hz, 5.7 Hz, 1F), –142.9 (dddd, J = 302.1 Hz, 53.2 Hz, 7.6 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for $C_{16}H_{15}F_4NO_2S$ + H: 362.0838, Found: 362.0834.

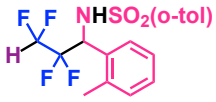


2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(4-methylphenyl)propyl)benzenesulfonamide (9k): The general procedure B was followed with **8k** (136.7 mg, 0.50 mmol), and the reaction mixture was stirred for 12 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9k** (127.6 mg, 68%) as white solid. mp: 144.8–145.5 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.29 (s, 3H), 2.43 (s, 3H), 4.65 (m, J = 12.1 Hz, 9.5 Hz, 1H), 5.32 (d, J = 9.5 Hz, 1H), 5.76 (dddd, J = 53.2 Hz, 52.3 Hz, 4.9 Hz, 1H), 6.95 (d, J = 7.8 Hz, 2H), 7.02 (d, J = 7.8 Hz, 2H), 7.12 (d, J = 7.7 Hz, 1H), 7.23 (dd, J = 8.0 Hz, 7.4 Hz, 1H), 7.38 (dd, J = 7.7 Hz, 7.4 Hz, 1H), 7.87 (d, J = 8.0

Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 21.2 (s), 57.5 (dd, *J* = 24.5 Hz, 23.6 Hz), 108.9 (dddd, *J* = 251.6 Hz, 31.0 Hz), 115.2 (dddd, *J* = 254.9 Hz, 24.5 Hz), 126.3 (s), 127.9 (s), 129.0 (s), 129.7 (s), 129.7 (s), 132.5 (s), 133.2 (s), 137.2 (s), 137.5 (s), 139.6 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.4 (br, *J* = 266.4 Hz, 1F), –129.2 (br, *J* = 266.4 Hz, 1F), –140.4 (dddd, *J* = 302.8 Hz, 52.3 Hz, 1F), –142.7 (dddd, *J* = 302.8 Hz, 53.2 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{17}F_4NO_2S$: 375.0916, Found: 375.0910.

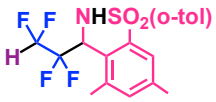


2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(3-methylphenyl)propyl)benzenesulfonamide (9l): The general procedure B was followed with **8l** (136.7 mg, 0.50 mmol), and the reaction mixture was stirred for 12 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9l** (132.1 mg, 70%) as white solid. mp: 90.1–91.0 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.21 (s, 3H), 2.40 (s, 3H), 4.63 (m, *J* = 12.8 Hz, 9.4 Hz, 1H), 5.26 (d, *J* = 9.4 Hz, 1H), 5.80 (dddd, *J* = 53.5 Hz, 53.0 Hz, 5.1 Hz, 1H), 6.75 (s, 1H), 6.89 (d, *J* = 7.5 Hz, 1H), 7.06–7.14 (3H), 7.24 (dd, *J* = 8.0 Hz, 7.5 Hz, 1H), 7.37 (ddd, *J* = 7.5 Hz, 7.5 Hz, 1.3 Hz, 1H), 7.88 (dd, *J* = 8.0 Hz, 1.3 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1(s), 21.3 (s), 57.7 (dd, *J* = 23.8 Hz), 108.9 (dddd, *J* = 252.7 Hz, 33.9 Hz), 115.2 (dddd, *J* = 256.6 Hz, 23.8 Hz), 124.9 (s), 126.2 (s), 128.8 (s), 129.0 (s), 129.8 (s), 130.3 (s), 131.8 (s), 132.5 (s), 133.3 (s), 137.2 (s), 137.5 (s), 138.9 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.4 (m, *J* = 265.8 Hz, 7.7 Hz, 4.9 Hz, 1F), 129.2 (m, *J* = 265.8 Hz, 12.8 Hz, 8.2 Hz, 7.7 Hz, 1F), –140.3 (ddd, *J* = 300.4 Hz, 53.0 Hz, 8.2 Hz, 4.9 Hz, 1F), –142.9 (ddd, *J* = 300.4 Hz, 53.5 Hz, 7.7 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{17}F_4NO_2S$: 375.0916, Found: 375.0912.

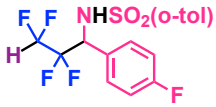


2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(2-methylphenyl)propyl)benzenesulfonamide (9m): The general procedure B was followed with **8m** (136.7 mg, 0.50 mmol), and the reaction mixture was stirred for 12 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9m** (105.3 mg, 56%) as white solid. mp: 119.1–119.9 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.10 (s, 3H), 2.43 (s, 3H), 5.08 (m, *J* = 10.5 Hz, 9.1 Hz, 1H), 5.32 (d, *J* = 9.1 Hz, 1H), 5.88 (dddd, *J* = 52.8 Hz, 52.6 Hz, 4.6 Hz, 1.8 Hz, 1H), 7.02 (d, *J* = 7.1 Hz, 1H), 7.10 (d, J = 7.8 Hz, 1H), 7.13–7.27 (4H), 7.36 (dd, *J* = 7.8 Hz, 7.5 Hz, 1H), 7.88 (d, *J* = 8.2 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 19.2 (s), 20.1 (s), 52.4 (dd, *J* = 22.9 Hz), 109.0 (dddd, *J* = 251.2 Hz, 33.5 Hz),

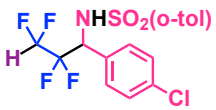
115.3 (dddd, J = 255.3 Hz, 25.0 Hz), 126.3 (s), 126.7 (s), 126.8 (s), 129.4 (s), 129.5 (s), 130.7 (s), 130.9 (s), 132.5 (s), 133.4 (s), 137.0 (s), 137.1 (s), 137.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.7 (m, J = 268.2 Hz, 10.5 Hz, 1F), –128.9 (m, J = 268.2 Hz, 9.1 Hz, 1F), –139.5 (ddd, J = 302.0 Hz, 52.6 Hz, 8.3 Hz, 1F), –143.5 (dddd, J = 302.0 Hz, 52.8 Hz, 8.7 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{17}F_4NO_2S$: 375.0916, Found: 375.0914.



2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(2,4,6-trimethylphenyl)propyl)benzenesulfonamide (9n): The general procedure C was followed with **8n** (30.1 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the yield of **9n** was a merely trace amount.

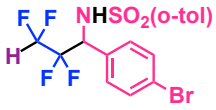


2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(4-fluorophenyl)propyl)benzenesulfonamide (9o): The general procedure A was followed with **8o** (138.7 mg, 0.50 mmol), and the reaction mixture was stirred for 6 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) gave **9o** (134.7 mg, 71%) as white solid. mp: 102.9–103.5 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.44 (s, 3H), 4.71 (m, J = 9.0 Hz, 1H), 5.41 (d, J = 9.0 Hz, 1H), 5.81 (dddd, J = 53.5 Hz, 52.0 Hz, 4.9 Hz, 1H), 6.91 (dd, J = 8.5 Hz, 8.4 Hz, 2H), 7.05 (dd, J = 8.4 Hz, 5.0 Hz, 2H), 7.14 (d, J = 7.5 Hz, 1H), 7.23 (dd, J = 7.9 Hz, 7.4 Hz, 1H), 7.40 (dd, J = 7.5 Hz, 7.4 Hz, 1H), 7.85 (d, J = 7.9 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 56.9 (dd, J = 25.5 Hz), 108.9 (dddd, J = 252.7 Hz, 250.8 Hz, 33.4 Hz, 32.5 Hz), 115.0 (dddd, J = 255.7 Hz, 254.8 Hz, 25.9 Hz, 25.0 Hz), 115.9 (s), 116.1 (s), 126.4 (s), 127.8 (d, J = 2.9 Hz), 129.6 (s), 130.0 (d, J = 8.8 Hz), 132.6 (s), 133.5 (s), 137.1 (s), 137.3 (s), 161.9 (s), 164.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –114.9 (tt, J = 8.5 Hz, 5.0 Hz, 1F), –129.4 (m, J = 6.4 Hz, 5.5 Hz, 2F), –140.7 (ddd, J = 302.8 Hz, 53.5 Hz, 6.4 Hz, 1F), –143.6 (m, J = 302.8 Hz, 52.0 Hz, 5.5 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{16}H_{14}F_5NO_2S$: 379.0655, Found: 379.0655.

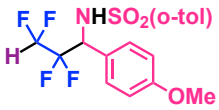


2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(4-chlorophenyl)propyl)benzenesulfonamide (9p): The general procedure B was followed with **8p** (146.9 mg, 0.50 mmol), and the reaction mixture was stirred

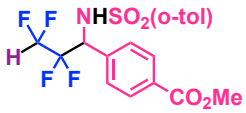
for 6 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9p** (140.5 mg, 71%) as white solid. mp: 119.7–120.3 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.46 (s, 3H), 4.70 (m, *J* = 9.6 Hz, 1H), 5.55 (d, *J* = 9.6 Hz, 1H), 5.79 (dddd, *J* = 52.5 Hz, 52.1 Hz, 5.3 Hz, 1H), 7.02 (d, *J* = 8.3 Hz, 2H), 7.15 (d, *J* = 8.3 Hz, 1H), 7.19 (d, *J* = 8.3 Hz, 2H), 7.23 (dd, *J* = 8.0 Hz, 7.6 Hz, 1H), 7.41 (ddd, *J* = 8.3 Hz, 7.6 Hz, 1.0 Hz, 1H), 7.84 (dd, *J* = 8.0 Hz, 1.0 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.2 (s), 57.1 (dd, *J* = 25.6 Hz), 108.9 (dddd, *J* = 252.3 Hz, 33.4 Hz), 115.0 (dddd, *J* = 255.7 Hz, 27.8 Hz), 126.4 (s), 129.2 (s), 129.5 (s), 129.6 (s), 130.5 (s), 132.7 (s), 133.5 (s), 135.7 (s), 137.2 (s), 137.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.2 (m, 2F), –139.5 (ddd, *J* = 302.3 Hz, 52.1 Hz, 5.1 Hz, 1F), –142.5 (ddd, *J* = 302.3 Hz, 52.5 Hz, 7.1 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{16}H_{14}ClF_4NO_2S$: 395.0370, Found: 395.0361.



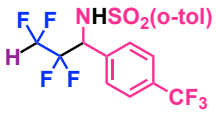
2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(4-bromorophenyl)propyl)benzenesulfonamide (9q): The general procedure C was followed with **8q** (33.8 mg, 0.10 mmol). ^{19}F NMR analysis revealed that the target compound **9q** was not generated.



2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(4-methoxyphenyl)propyl)benzenesulfonamide (9r): The general procedure B was followed with **8r** (144.7 mg, 0.50 mmol), and the reaction mixture was stirred for 12 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9r** (58.7 mg, 30%) as white solid. mp: 127.9–128.5 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.43 (s, 3H), 3.76 (s, 3H), 4.64 (m, *J* = 12.2 Hz, 9.2 Hz, 1H), 5.34 (d, *J* = 9.2 Hz, 1H), 5.77 (dddd, *J* = 52.6 Hz, 52.2 Hz, 5.3 Hz, 1H), 6.72 (d, *J* = 8.8 Hz, 2H), 6.98 (d, *J* = 8.8 Hz, 2H), 7.13 (d, *J* = 7.6 Hz, 1H), 7.23 (dd, *J* = 7.9 Hz, 7.6 Hz, 1H), 7.38 (ddd, *J* = 7.6 Hz, 7.6 Hz, 1.0 Hz, 1H), 7.87 (dd, *J* = 7.9 Hz, 1.0 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 55.4 (s), 57.2 (dd, *J* = 24.0 Hz), 108.9 (dddd, *J* = 250.8 Hz, 32.8 Hz), 114.4 (s), 115.2 (dddd, *J* = 254.8 Hz, 25.4 Hz), 123.9 (s), 126.2 (s), 129.3 (s), 129.6 (s), 132.6 (s), 133.3 (s), 137.2 (s), 137.5 (s), 160.3 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.9 (m, *J* = 266.9 Hz, 7.2 Hz, 3.3 Hz, 1F), –129.1 (m, *J* = 266.9 Hz, 12.2 Hz, 8.8 Hz, 7.2 Hz,1F), –140.5 (ddd, *J* = 301.9 Hz, 52.2 Hz, 8.8 Hz, 3.3 Hz, 1F), –142.8 (dddd, *J* = 301.9 Hz, 52.6 Hz, 7.2 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{17}F_4NO_3S$: 391.0865, Found: 391.0860.

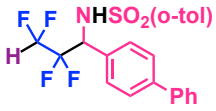


Methyl 4-(2,2,3,3-tetrafluoro-1-((2-methylphenyl)sulfonamido)propyl)benzoate (9s): The general procedure B was followed with **8s** (158.7 mg, 0.50 mmol), and the reaction mixture was stirred for 6 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9s** (167.8 mg, 80%) as white solid. mp: 150.1–150.8 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.43 (s, 3H), 3.92 (s, 3H), 4.78 (m, *J* = 12.1 Hz, 9.6 Hz, 1H), 5.46 (d, *J* = 9.6 Hz, 1H), 5.83 (dddd, *J* = 53.0 Hz, 52.5 Hz, 5.0 Hz, 1H), 7.11 (d, *J* = 7.7 Hz, 1H), 7.16 (d, *J* = 8.1 Hz, 2H), 7.22 (dd, *J* = 8.1 Hz, 7.5 Hz, 1H), 7.38 (ddd, *J* = 7.7 Hz, 7.5 Hz, 1.2 Hz, 1H), 7.86 (dd, *J* = 8.1 Hz, 1.2 Hz, 1H), 7.89 (d, *J* = 8.1 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 52.5 (s), 57.3 (dd, *J* = 25.4 Hz), 108.8 (dddd, *J* = 251.6 Hz, 33.5 Hz), 114.9 (dddd, *J* = 256.8 Hz, 26.3 Hz), 126.4 (s), 128.2 (s), 129.6 (s), 130.1 (s), 131.2 (s), 132.7 (s), 133.5 (s), 136.6 (s), 137.1 (s), 137.2 (s), 166.3 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –127.5 (m, *J* = 272.0 Hz, 7.5 Hz, 3.5 Hz, 1F), –128.2 (m, *J* = 272.0 Hz, 12.1 Hz, 7.5 Hz, 6.9 Hz, 1F), –139.1 (dddd, *J* = 301.7 Hz, 52.5 Hz, 6.9 Hz, 3.5 Hz, 1F), –142.6 (dddd, *J* = 301.7 Hz, 53.0 Hz, 7.5 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{18}H_{17}F_4NO_4S$: 419.0814, Found: 419.0810.

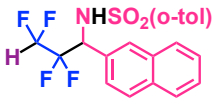


2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(4-(trifluoromethyl)phenyl)propyl)benzenesulfonamide (9t): The general procedure A was followed with **8t** (163.7 mg, 0.50 mmol), and the reaction mixture was stirred for 6 h. Purification by silica gel column chromatography (elute: CH_2Cl_2) gave **9t** (182.7 mg, 85%) as white solid. mp: 131.9–132.6 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.46 (s, 3H), 4.82 (m, *J* = 8.7 Hz, 1H), 5.55 (d, *J* = 8.7 Hz, 1H), 5.82 (dddd, *J* = 53.0 Hz, 52.6 Hz, 4.4 Hz, 1H), 7.11 (d, *J* = 7.4 Hz, 1H), 7.21 (dd, *J* = 7.8 Hz, 7.3 Hz, 1H), 7.22 (d, *J* = 7.9 Hz, 2H), 7.38 (dd, *J* = 7.4 Hz, 7.3 Hz, 1H), 7.46 (d, *J* = 7.9 Hz, 2H), 7.80 (d, *J* = 7.8 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.2 (s), 57.2 (dd, *J* = 25.2 Hz, 23.6 Hz), 108.8 (dddd, *J* = 252.8 Hz, 251.5 Hz, 33.5 Hz, 32.9 Hz), 114.9 (dddd, *J* = 255.3 Hz, 254.7 Hz, 27.1 Hz, 25.6 Hz), 123.7 (q, *J* = 272.1 Hz), 125.9 (q, *J* = 3.9 Hz), 126.4 (s), 128.7 (s), 129.6 (s), 131.7 (q, *J* = 32.8 Hz), 132.7 (s), 133.6 (s), 135.7 (s), 137.1 (s), 137.2 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –65.7 (s, 3F), –127.0 (m, *J* = 270.9 Hz, 7.0 Hz, 6.9 Hz, 1F), –127.9 (m, *J* = 270.9 Hz, 8.3 Hz, 2.3 Hz, 1F), –138.9 (m, *J* = 303.0 Hz, 52.6 Hz, 7.0 Hz, 2.3 Hz, 1F), –142.1 (dddd, *J* = 303.0 Hz, 53.0 Hz, 8.3 Hz, 6.9 Hz, 1F). **HRMS (CI)**: *m/z* Calcd for

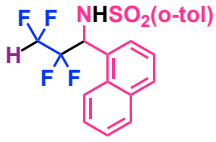
$C_{17}H_{14}F_4NO_2S$ + H: 430.0712, Found: 430.0704.



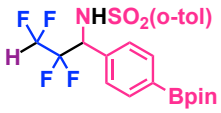
2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-biphenylpropyl)benzenesulfonamide (9u): The general procedure A was followed with **8u** (167.7 mg, 0.50 mmol), and the reaction mixture was stirred for 6 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 92:8) gave **9u** (166.2 mg, 76%) as white solid. mp: 115.4–116.0 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.46 (s, 3H), 4.77 (m, *J* = 9.3 Hz, 1H), 5.34 (d, *J* = 9.3 Hz, 1H), 5.83 (dddd, *J* = 53.5 Hz, 52.6 Hz, 5.0 Hz, 1H), 7.10 (d, *J* = 7.3 Hz, 1H), 7.13 (d, *J* = 8.4 Hz, 2H), 7.22 (dd, *J* = 7.9 Hz, 7.6 Hz, 1H), 7.33-7.70 (m, 8H), 7.87 (dd, *J* = 7.9 Hz, 1.0 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.2 (s), 57.5 (dd, *J* = 23.8 Hz), 108.9 (dddd, *J* = 251.2 Hz, 33.7 Hz), 115.2 (dddd, *J* = 255.7 Hz, 25.4 Hz), 126.3 (s), 127.2 (s), 127.7 (s), 128.0 (s), 128.5 (s), 129.0 (s), 129.7 (s), 130.7 (s), 132.6 (s), 133.3 (s), 137.1 (s), 137.5 (s), 140.0 (s), 142.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.4 (m, 2F), –140.0 (dddd, *J* = 302.2 Hz, 52.6 Hz, 5.4 Hz, 1F), –142.1 (dddd, *J* = 302.2 Hz, 53.5 Hz, 7.2 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{22}H_{19}F_4NO_2S$: 437.1073, Found: 437.1069.



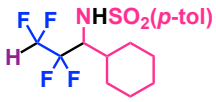
2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(naphthalene-2-yl)propyl)benzenesulfonamide (9v): The general procedure B was followed with **8v** (154.7 mg, 0.50 mmol), and the reaction mixture was stirred for 12 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9v** (150.2 mg, 73%) as white solid. mp: 116.0–116.5 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.39 (s, 3H), 4.87 (m, *J* = 9.1 Hz, 1H), 5.41 (d, *J* = 9.1 Hz, 1H), 5.82 (dddd, *J* = 52.8 Hz, 52.3 Hz, 5.4 Hz, 1H), 6.95 (d, *J* = 7.8 Hz, 1H), 7.15 (dd, *J* = 7.7 Hz, 7.3 Hz, 1H), 7.18–7.24 (2H), 7.43 (s, 1H), 7.46–7.54 (2H), 7.67 (d, *J* = 8.1 Hz, 1H), 7.72 (d, *J* = 8.6 Hz, 1H), 7.78 (d, *J* = 8.1 Hz, 1H), 7.87 (d, *J* = 7.7 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.0 (s), 57.9 (dd, *J* = 24.4 Hz), 108.9 (dddd, *J* = 254.8 Hz, 32.1 Hz), 115.3 (dddd, *J* = 253.0 Hz, 25.8 Hz), 124.3 (s), 126.2 (s), 126.8 (s), 127.2 (s), 127.7 (s), 128.3 (s), 128.4 (s), 129.0 (s), 129.1 (s), 129.6 (s), 132.5 (s), 132.9 (s), 133.2 (s), 133.4 (s), 137.1 (s), 137.3 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.2 (m, 2F), –140.1 (dd, *J* = 301.4 Hz, 52.3 Hz, 1F), –142.5 (dd, *J* = 301.4 Hz, 52.8 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{20}H_{17}F_4NO_2S$: 411.0916, Found: 411.0915.



2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(naphthalene-1-yl)propyl)benzenesulfonamide (9w): The general procedure B was followed with **8w** (154.7 mg, 0.50 mmol), and the reaction mixture was stirred for 12 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9w** (82.3 mg, 40%) as white solid. mp: 144.5–145.1 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.34 (s, 3H), 5.68-5.77 (2H), 5.92 (dddd, *J* = 52.7 Hz, 52.3 Hz, 4.9 Hz, 1H), 6.84 (d, *J* = 7.5 Hz, 1H), 6.85 (dd, *J* = 7.7 Hz, 1H), 7.05 (dd, *J* = 7.9 Hz, 7.7 Hz, 1H), 7.36 (dd, *J* = 7.7 Hz, 7.5 Hz, 1H), 7.43–7.48 (3H), 7.71–7.77 (4H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 51.5 (br), 109.0 (dddd, *J* = 250.6 Hz, 31.6 Hz), 115.4 (dddd, *J* = 256.2 Hz, 26.0 Hz), 122.0 (s), 125.0 (s), 125.7 (br), 126.0 (s), 126.2 (s), 127.2 (s), 128.4 (s), 128.8 (s), 129.4 (s), 130.1 (s), 131.0 (s), 132.1 (s), 132.9 (s), 133.5 (s), 136.7 (s), 136.9 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.2 (br, 2F), –139.3 (dd, *J* = 301.8 Hz, 52.3 Hz, 1F), –142.8 (dd, *J* = 301.8 Hz, 52.7 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{20}H_{17}F_4NO_2S$: 411.0916, Found: 411.0913.



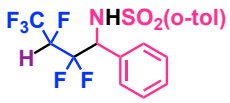
2-Methyl-*N*-(2,2,3,3-tetrafluoro-1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)propyl)benzenesulfonamide (9x): The general procedure B was followed with **8x** (192.6 mg, 0.50 mmol), and the reaction mixture was stirred for 6 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9x** (175.4 mg, 72%) as white solid. mp: 139.8–140.5 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 1.34 (s, 12H), 2.42 (s, 3H), 4.70 (m, *J* = 9.5 Hz, 1H), 5.27 (d, *J* = 9.5 Hz, 1H), 5.78 (dddd, *J* = 52.8 Hz, 52.4 Hz, 5.6 Hz, 1H), 7.06 (d, *J* = 8.0 Hz, 2H), 7.11 (d, *J* = 7.8 Hz, 1H), 7.23 (dd, *J* = 8.1 Hz, 7.6 Hz, 1H), 7.37 (ddd, *J* = 7.8 Hz, 7.6 Hz, 1.1 Hz, 1H), 7.66 (d, *J* = 8.0 Hz, 2H), 7.87 (dd, *J* = 8.1 Hz, 1.1 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.2 (s), 25.0 (s), 57.7 (dd, *J* = 23.9 Hz), 84.2 (s), 108.8 (dddd, *J* = 251.7 Hz, 31.8 Hz), 115.1 (dddd, *J* = 254.5 Hz, 24.5 Hz), 126.3 (s), 127.3 (s), 129.7 (s), 132.6 (s), 133.4 (s), 134.6 (s), 135.4 (s), 137.1 (s), 137.4 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –128.5 (m, 2F), –140.0 (ddd, *J* = 301.4 Hz, 52.4 Hz, 6.0 Hz, 1F), –142.7 (ddd, *J* = 301.4 Hz, 52.8 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{22}H_{26}F_4NO_4SB$: 487.1612, Found: 487.1614.



2-Methyl-*N*-(1-cyclohexyl-2,2,3,3-tetrafluoropropyl)benzenesulfonamide (9y): The general procedure B was followed with **8y** (132.7 mg, 0.50 mmol), and the reaction mixture was stirred for 12 h. Purification by silica gel column chromatography (elute: hexane:AcOEt = 9:1) and HPLC gave **9y** (113.9 mg, 62%) as white solid. mp: 96.6–96.9 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 0.98–1.83 (11H), 2.44 (s, 3H), 3.76 (m, *J* = 10.3 Hz, 1H), 4.67 (d, *J* = 10.3 Hz, 1H), 5.72 (m, *J* = 53.6 Hz, 53.2 Hz, 8.9 Hz, 1.6 Hz, 1H), 7.32 (d, *J* = 8.3 Hz, 2H), 7.74 (d, *J* = 8.3 Hz, 2H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 21.7 (s), 25.8 (s), 26.0 (s), 26.3 (s), 27.2 (s), 30.5 (s), 37.3 (s), 57.7 (dd, *J* = 25.5 Hz, 20.4 Hz), 109.1 (dddd, *J* = 244.1 Hz), 116.4 (dddd, *J* = 248.4 Hz), 127.2 (s), 129.9 (s), 137.9 (s), 144.2 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –124.3 (m, *J* = 270.7 Hz, 7.2 Hz, 1F), –127.9 (m, *J* = 270.7 Hz, 9.3 Hz, 9.0 Hz, 1F), –138.2 (ddd, *J* = 299.7 Hz, 53.2 Hz, 9.3 Hz, 1F), –144.2 (dddd, *J* = 299.7 Hz, 53.6 Hz, 9.0 Hz, 7.2 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{16}H_{21}F_4NO_2S$: 367.1229, Found: 367.1228.

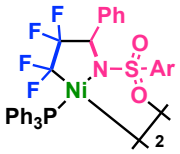
2-Methyl-*N*-(2,3,3-trifluoro-1-phenyl)propyl)benzenesulfonamide: A toluene solution (3.0 mL) of $Ni(cod)_2$ (27.5 mg, 0.10 mmol), PPh_3 (26.2 mg, 0.10 mmol), **8e** (1.0 mmol), and Et_2SiH_2 (88.2 mg, 1.0 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). Then, trifluoroethylene (2.0 atm) was charged into the autoclave reactor. The reaction mixture was stirred at 120 ºC for 12 h. The unreacted trifluoroethylene was purged from the autoclave reactor. (caution: The reaction mixture must be handle in a well-ventilated fume hood.) The reaction mixture was quenched with MeOH and filtrated to remove insoluble residue. All volatiles were removed under reduced pressure, and the crude product was purified by silica gel column chromatography and high performance liquid chromatography (HPLC) to give the mixture of the title product (the diasteremer) in 60% (211.9 mg, d.r = 12:1) and 2-methyl-*N*-(2,2,3-trifluoro-1-phenyl)propyl)benzenesulfonamide (the regioisomer). NMR spectra and HRMS of the major product was the following data: **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.43 (s, 3H), 4.53 (ddd, *J* = 25.9 Hz, 8.7 Hz, 4.0 Hz, 1H), 4.82 (m, *J* = 8.2 Hz, 5.2 Hz, 4.0 Hz, 1H), 5.34 (d, *J* = 8.7 Hz, 1H), 5.37 (ddt, *J* = 53.7 Hz, 5.2 Hz, 4.8 Hz, 1H), 7.01 (d, *J* = 8.2 Hz, 2H), 7.13 (d, *J* = 7.6 Hz, 1H), 7.18–7.27 (4H), 7.38 (ddd, J = 7.6 Hz, 7.5 Hz, 1,2 Hz, 1H), 7.87 (dd, *J* = 7.9 Hz, 1.2 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (d, *J* = 3.6 Hz), 56.5 (dt, *J* = 19.7 Hz, 4.1 Hz), 91.3 (dt, *J* = 188.0 Hz, 27.3 Hz), 112.3 (ddt, *J* = 245.5 Hz, 28.1 Hz, 4.9 Hz), 126.3

(s), 127.7 (s), 129.1 (s), 129.1 (s), 129.6 (s), 132.6 (s), 133.2 (s), 133.9 (s), 137.1 (s), 137.7 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –133.8 (tm, J = 25.9 Hz, 13.1 Hz, 4.8 Hz, 1F), –214.8 (ddd, J = 53.7 Hz, 13.1 Hz, 8.2 Hz, 2F). **HRMS (CI)**: *m/z* Calcd for $C_{16}H_{16}F_3NO_2S$ + H: 344.0932, Found: 344.0928.



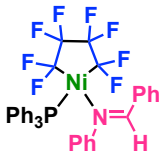
***N*-(2,2,3,4,4,4-Hexafluoro-1-phenylbutyl)-2-methylbenzenesulfonamide:** A toluene solution (3.0 mL) of $Ni(cod)_2$ (55.0 mg, 0.20 mmol), PPh_3 (52.5 mg, 0.20 mmol), **8e** (1.0 mmol), and Et_2SiH_2 (88.2 mg, 1.0 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). Then, hexafluoropropene (5.0 atm) was charged into the autoclave reactor. The reaction mixture was stirred at 120 ºC for 12 h. The unreacted hexafluoropropene was purged from the autoclave reactor. (caution: The reaction mixture must be handle in a well-ventilated fume hood.) The reaction mixture was quenched with MeOH and filtrated to remove insoluble residue. All volatiles were removed under reduced pressure. The NMR experiments of the crude reaction mixture showed the title product was generated in 16% yield (7.2:1 d.r). The crude product was purified by silica gel column chromatography and high performance liquid chromatography (HPLC) to give the major titled product (25.3 mg, 6%) as white solid. mp: 159.1–159.7 °C. **^{1}H NMR** (400 MHz, in $CDCl_3$, rt, δ/ppm): 2.49 (s, 3H), 4.48 (m, J = 43.2 Hz, 1H), 4.80 (m, 1H), 5.31 (d, J = 9.0 Hz, 1H), 7.12–7.26 (7H), 7.30 (ddd, J = 7.6 Hz, 7.5 Hz, 0.6 Hz, 1H), 7.85 (dd, J = 7.9 Hz, 1.1 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.1 (s), 59.4 (dd, J = 22.0 Hz, 21.3 Hz), 83.8 (ddq, J = 195.9 Hz, 35.1 Hz, 34.6 Hz), 117.1 (dq, J = 252.6 Hz, 25.1 Hz), 120.7 (dd, J = 283.7 Hz, 26.1 Hz), 126.2 (s), 128.0 (s), 129.4 (s), 129.6 (s), 129.9 (s), 132.4 (d, J = 5.4 Hz), 132.6 (s), 133.3 (s), 137.2 (s), 137.7 (s). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –76.4 (m, J = 11.0 Hz, 9.7 Hz, 3F), –121.9 (m, J = 265.0 Hz, 9.7 Hz, 2.8 Hz, 1F), –125.2 (m, J = 265.0 Hz, 11.0 Hz, 3.3 Hz, 1F), –214.6 (m, J = 43.2 Hz, 3.3 Hz, 2.8 Hz, 1F). **HRMS (EI)**: m/z Calcd for $C_{17}H_{15}F_6NO_2S$: 411.0728, Found: 411.0724.

General procedure for the substrate scope with the respect to the other fluorinated olefins: A toluene solution (0.5 mL) of $Ni(cod)_2$ (2.8 mg, 0.010 mmol), PPh_3 (2.0 mg, 0.010 mmol), **8e** (0.10 mmol), and Et_2SiH_2 (0.10 mmol) was transferred into a pressure-tight NMR tube. Then, a given fluorinated olefin was charged into the reaction tube. The reaction mixture was heated to 120 ºC for 6 h. The reaction mixture was quenched with MeOH, and C_6D_6 and α,α,α-trifluorotoluene as the internal standard were added to estimate the yield of the desired product by ^{19}F NMR analysis.



Preparation of [($CF_2CF_2CHPhNSO_2$(*o*-tol))Ni(PPh_3)]$_2$ (*syn*-VII): A toluene solution (9.0 mL) of Ni(cod)$_2$ (137.5 mg, 0.50 mmol), PPh_3 (131.1 mg, 0.50 mmol), and **8e** (129.7 mg, 0.50 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). Then, TFE (1.5 atm, >3.4 mmol) was charged into the reactor. The reaction mixture was stirred at 60 ºC for 7 h. All volatiles were removed under reduced pressure, and the crude product was purified by recrystallization from toluene and pentane to afford a single crystal of ***syn*-VII** as a red solid (517.2 mg, 76%). **^{1}H NMR** (400 MHz, in toluene-d_8, rt, δ/ppm): 2.69 (s, 6H), 4.64 (br, 2H, -NC*H*Ph-), 6.75 (d, J = 7.5 Hz, 4H, aromatic-*H*), 6.89 (dd, J = 7.5 Hz, 7.1 Hz, 2H, aromatic-*H*), 6.98–7.05 (24H, aromatic-*H*), 7.36 (br, 4H, aromatic-*H*), 7.66–7.72 (12H, aromatic-*H*), 8.06 (br, 2H, aromatic-*H*). **^{13}C{^{1}H} NMR** (100 MHz, in toluene-d_8, rt, δ/ppm): 21.3 (s), 62.3 (dd, J = 31.1 Hz, 23.7 Hz), 128.3 (s), 128.5 (s), 129.0 (s), 129.5 (s), 130.0 (s), 131.0 (s), 132.5 (s), 132.7 (s). Resonances attributable to the CF_2CF_2 moiety could not be detected due to multiple ^{13}C–^{19}F couplings and resonances attributable to the aromatic-C could not be detected due to the overlap with toluene-d_8. **^{19}F NMR** (376 MHz, in toluene-d_8 rt, δ/ppm): –90.8 (br, J = 210.1 Hz, 2F, α-CF_2-), –96.2 (br, 2F, α-CF_2-), –119.6 (br, J = 227.6 Hz, 2F, β-CF_2-), –124.7 (br, J = 227.6 Hz, 2F, β-CF_2-). **^{31}P NMR** (162 MHz, in toluene-d_8, rt, δ/ppm): 27.7 (br, 2P, -*P*Ph_3). **Anal. Calcd** for $C_{68}H_{56}F_8N_2Ni_2O_4P_2S_2$: C, 60.03; H, 4.15; N 2.06: O; 4.70. Found: C, 60.24; H, 4.35; N, 2.04. **X-ray data** for the complex ***syn*-VII**. M = 1360.65, platelet, red, monoclinic, *C*2/c, a = 22.7862(2) Å, b = 15.58238(10) Å, c = 24.5597(2) Å, β = 115.6281(11), V = 7862.35(13) Å^3, Z = 4, Dcalcd = 1.383 g/cm^3, T = –150 °C, R_1 (wR_2) = 0.0387 (0.1031).

Reaction of *syn*-VII with Et_2SiH_2: A C_6D_6 solution (0.5 mL) of ***syn*-VII** (40.9 mg, 0.03 mmol) and Et_2SiH_2 (26.5 mg, 0.30 mmol) was remained at a given temperature, and the reaction mixure was quenched with MeOH. The yield of **9e** was determined by ^{19}F NMR analysis using α,α,α-trifluorotoluene as the internal standard.



Preparation of ($CF_2CF_2CF_2CF_2$)Ni(PPh_3)(PhN=CHPh) (VIII): A toluene solution (15.0 mL) of

$Ni(cod)_2$ (275.2 mg, 1.0 mmol), PPh_3 (262.3 mg, 1.0 mmol), and **8h** (181.6 mg, 1.0 mmol) was transferred into an autoclave reactor (volume: 50.0 mL). Then, TFE (1.5 atm) was charged into the reactor. The reaction mixture was stirred at 60 ºC for 7 h. All volatiles were removed under reduced pressure, and the crude product was washed with hexane, followed by recrystallization from toluene and pentane, to afford a single crystal of **VIII** as a yellow solid (104.1 mg, 15%). **^{1}H NMR** (400 MHz, in C_6D_6, rt, δ/ppm): 6.84–6.89 (6H), 6.93–7.08 (7H), 7.27 (dd, J = 7.3 Hz, 2H), 7.35 (dd, J = 9.1 Hz, 8.8 Hz, 6H), 7.52 (br, 3H), 8.92 (d, J = 6.9 Hz, 2H). **^{13}C{^{1}H} NMR** (100 MHz, in C_6D_6, rt, δ/ppm): 123.9 (s), 128.6 (s), 129.0 (s), 129.1 (s), 129.3 (s), 130.4 (d, J = 1.5 Hz), 130.8 (s), 131.5 (s), 133.5 (s), 134.7 (d, J = 10.9 Hz), 149.2 (s), 168.4 (s). Resonances attributable to the CF_2CF_2 moiety could not be detected due to multiple ^{13}C–^{19}F couplings. **^{19}F NMR** (376 MHz, in C_6D_6, rt, δ/ppm): –98.0 (m, J = 278.6 Hz, 25.7 Hz, 1F, α-CF_2-), –99.6 (m, J = 278.6 Hz, 24.8 Hz, 1F, α-CF_2-), –106.6 (dd, J = 267.7 Hz, 25.4 Hz 1F, α-CF_2-), –108.4 (dd, J = 267.7 Hz, 24.3 Hz 1F, α-CF_2-), –138.6 (br, J = 249.0 Hz, 2F, β-CF_2-), –140.7 (m, J = 249.0 Hz, 2F, β-CF_2-). **^{31}P NMR** (162 MHz, in C_6D_6, rt, δ/ppm): 25.4 (m, J = 25.7 Hz, 25.3 Hz, 24.8 Hz, 24.3 Hz, 1P, -PPh$_3$). **Anal. Calcd** for $C_{35}H_{26}F_8NNiP$: C, 59.86; H, 3.73; N 1.99. Found: C, 59.93; H, 3.73; N, 2.03. **X-ray data** for the complex **VIII**. M = 702.25, block, yellow, triclinic, $P\bar{1}$, a = 10.8661(3) Å, b = 16.6266(4) Å, c = 18.4750(5) Å, α = 106.599(2), β = 92.800(2), γ = 102.873(2), V = 3095.63(15) Å^3, Z = 2, Dcalcd = 1.507 g/cm^3, T = –150 °C, R_1 (wR_2) = 0.0344 (0.0796).

Reaction of VIII with Et_2SiH_2: A C_6D_6 solution (0.5 mL) of **VIII** (7.0 mg, 0.01 mmol) and Et_2SiH_2 (0.10 mmol) was heated at 120 ºC for 6 h, and the reaction mixture was quenched with MeOH. The target product **9h** was not determined by ^{19}F NMR using α,α,α-trifluorotoluene as the internal standard.

Preparation of Trifluoro Allylic Amine (11k): A THF solution (0.5 mL) of ^{i}Pr$_2$NH (91.1 mg, 0.90 mmol) was added to a hexane solution of ^{n}BuLi (1.6 M, 0.90 mmol) at –78 ºC, and the reaction mixture was stirred at 0 ºC for 1 h to prepare lithium diisopropyl amide. Then, a THF solution (0.5 mL) of **9k** (112.6 mg, 0.30 mmol) was added to the reaction mixture and stirred at –20 ºC for 2 h. After quenched with MeOH, the crude product was further purified by filtration and silica gel column chromatography (hexane:AcOEt = 95:5) to afford trifluoro allylic amine (**11k**: 87.4 mg, 82%) as colorless oil. **^{1}H NMR**

(400 MHz, in $CDCl_3$, rt, δ/ppm): 2.33 (s, 3H), 2.64 (s, 3H), 5.09 (d, *J* = 7.7 Hz, 1H,), 5.26 (ddm, *J* = 27.3 Hz, 7.7 Hz, 1H), 7.14–7.19 (4H), 7.31–7.34 (2H), 7.49 (dd, *J* = 7.4 Hz, 7.1 Hz, 1H), 7.99 (d, *J* = 7.7 Hz, 1H). **^{13}C NMR** (100 MHz, in $CDCl_3$, rt, δ/ppm): 20.2 (s), 21.2 (s), 52.6 (dt, *J* = 20.6 Hz, 2.13 Hz), 126.3 (ddd, *J* = 238.4 Hz, 51.0 Hz, 15.1 Hz), 126.4 (s), 126.8 (s), 129.6 (s), 129.9 (s), 132.2 (s), 132.4 (s), 132.7 (s), 133.4 (s), 137.3 (s), 137.8 (s), 139.0 (s), 152.7 (td, *J* = 44.0 Hz, 13.8 Hz). **^{19}F NMR** (376 MHz, in $CDCl_3$, rt, δ/ppm): –104.7 (m, *J* = 76.5 Hz, 31.0 Hz, 1F), –121.2 (dd, *J* = 116.1 Hz, 76.5 Hz, 1F), –188.4 (m, *J* = 116.1 Hz, 31.0 Hz, 1F). **HRMS (EI)**: *m/z* Calcd for $C_{17}H_{16}F_3NO_2S$: 355.0854, Found: 355.0856.

4.10 References and Notes

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Conclusion

In this thesis, studies on the efficient and straightforward transformation of industrially available TFE with nickel catalysts for the synthesis of a variety of highly fluorinated organic compounds are described. These nickel-catalyzed reactions proceed chemoselectively via the oxidative cyclization of TFE and a π-component as the key reaction step.

In Chapter 2, the Ni(0)-catalyzed chemoselective cross-trimerization reaction of TFE, ethylene, and aldehydes is demonstrated, which affords a variety of fluorine-containing ketones with an atomic efficiency of 100%. Based on the results of stoichiometric reactions, it is feasible to conclude that this catalytic reaction proceeds via the oxidative cyclization of TFE and ethylene, i.e., a combination of electron-deficient and –rich π-components, as the key reaction step.

In Chapter 3, the Ni(0)-catalyzed three-component coupling reaction of TFE, aldehydes, and silanes is disclosed, which affords various fluorine-containing silyl ethers that can be transformed into valuable trifluorovinyl compounds and organic silicone compounds via a deprotonation using LDA. Mechanistic studies on this catalytic reaction reveal that an oxa-nickelacycle generated from TFE and an aldehyde, i.e., a combination of two electron-deficient π-components, is the key intermediate. In addition, a sterically demanding phosphine ligand is important for the selective oxidative cyclization of TFE and an aldehyde, as the oxidative cyclization of two molecules of TFE is thus suppressed.

In Chapter 4, the Ni(0)-catalyzed three-component coupling reaction of TFE, *N*-sulfonyl-substituted imines, and silanes is reported, which furnishes a variety of fluorine-containing amines. Stoichiometric reactions revealed that an aza-nickelacycle, generated from TFE and *N*-sulfonyl-substituted imines, is the key intermediate in this reaction. The *N*-sulfonyl group on the imines is essential for the selective oxidative cyclization of TFE and the imines due to (i) the enhancement of the coordination ability of the imines by back-donation from Ni(0), and (ii) the thermodynamic stabilization of the aza-nickelacycle by the coordination of the oxygen atom of the *N*-sulfonyl group to the nickel center.

The studies in this thesis provided new synthetic strategic routes from TFE, which is an environmentally friendly feedstock in the fluorine industry, to a variety of highly fluorinated organic compounds. The three developed nickel-catalyzed transformations proceed via the selective oxidative cyclization of TFE and a π-component including ethylene, aldehydes, and *N*-sulfonyl-substituted imines as the key C–C-bond-formation step.

List of Publications

1. Nickel-Catalyzed Formation of Fluorine-Containing Ketones via the Selective Cross-Trimerization Reaction of Tetrafluoroethylene, Ethylene, and Aldehydes
   Masato Ohashi, Hiroshi Shirataki, Kotaro Kikushima, Sensuke Ogoshi
   J. Am. Chem. Soc. **2015**, *137*, 6496–6499.

2. Nickel-catalyzed Three-component Coupling Reaction of Tetrafluoroethylene and Aldehydes with Silanes via Oxa-Nickelacycles
   Hiroshi Shirataki, Masato Ohashi, Sensuke Ogoshi
   Eur. J. Org. Chem. **2018**, ASAP Articles (10.1002/ejoc.201801721)

3. Ni(0)-Catalyzed Three-Component Coupling Reaction of Tetrafluoroethylene and *N*-Sulfonyl-Substituted Imines with Silanes via Aza-nickelacycles
   Hiroshi Shirataki, Takafumi Ono, Masato Ohashi, Sensuke Ogoshi
   Org. Lett. **2018**, ASAP Articles (10.1021/acs.orglett.8b03674)