




1. PRF#: 58839-ND1

2. Title: Electrocatalytic C–H Functionalization of Hydrocarbons

3. Principal Investigator: Harry B. Gray, California Institute of Technology

4. Co-Principal Investigator: Brian M. Stoltz, California Institute of Technology

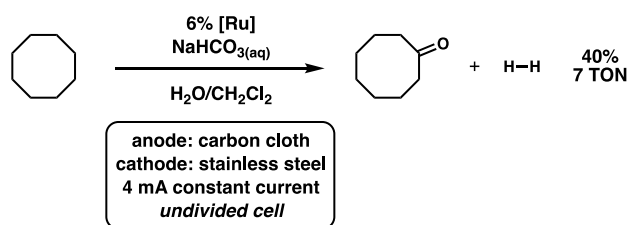
**Overview:** This project seeks to develop versatile and robust electrocatalytic methods for the C–H functionalization (particularly oxidation) of hydrocarbons. We have identified two homogeneous catalyst systems that can oxidize hydrocarbon substrates in synthetically-relevant quantities using a simple electrosynthetic apparatus; however, our efforts to achieve these transformations with heterogeneous catalysts have been limited by catalyst instability. Our goals for the second year of this award are to further develop the homogeneous catalyst systems for a wide variety of hydrocarbons and to address the instability of the heterogeneous system.

substrate	onset potential (V vs Pt <sup>2</sup> )
	1.2
	1.7
	2.1

**Fig. 1** Onset potentials of various hydrocarbons using the FeNi LDH catalyst

**Research progress in year 1:** Initial experiments with the

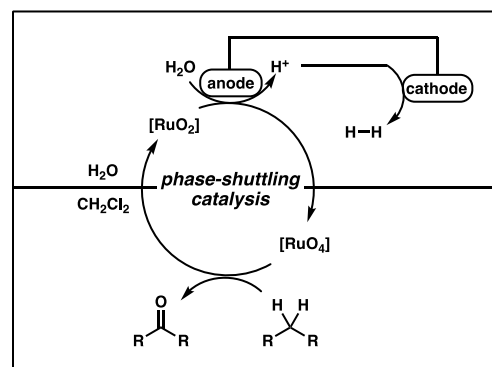
Ni/Fe layered double-hydroxide (LDH) electrocatalyst reproduced the initial results cited in the research plan for this award. The LDH is able to oxidize alkanes in a potential dependent fashion, with ethylbenzene, 2-methylpentane, and cyclohexane having onset potentials of 1.2, 1.7, and 2.1 V vs a platinum wire pseudoreference in acetonitrile (Fig. 1). However, prolonged bulk electrolysis leads to decomposition of the electrode-catalyst composite and insufficient quantities of product are generated for a synthetically-useful process. The stability of the LDH catalyst in water oxidation is contingent on constant regeneration by aqueous hydroxide (e.g. pH 12 KOH solution), a reaction condition that's not immediately compatible with nonpolar organic molecules such as alkanes.



**Fig. 2** Example reaction of the ruthenium-catalyzed C–H electrooxidation

cyclooctenone, with reasonable turnover numbers (7 comparing ketone to starting material, 14 considering the stepwise hydroxylation-alcohol oxidation process, fig. 2). Our working hypothesis for the biphasic oxidation mechanism is shown in figure 3, where ruthenium dioxide, dispersed in the aqueous layer, is oxidized at the anode to organic-soluble ruthenium tetroxide, which is able to

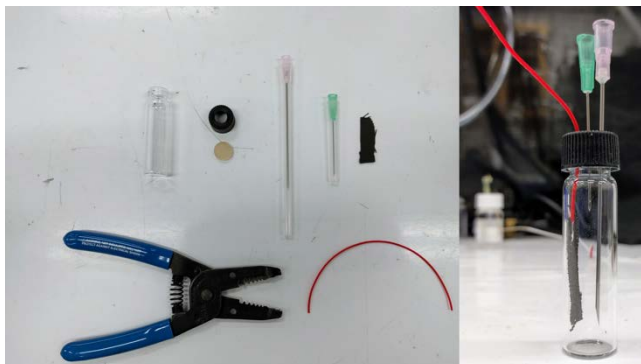
In response to the intrinsic instability of the LDH catalyst, a significant portion of this reporting period was spent investigating alternative inorganic salts to serve as robust C–H oxidation electrocatalysts. After screening a variety of salts of ruthenium, chromium, iron, and iridium, we found that ruthenium salts catalyze the C–H oxidation of a model hydrocarbon, cyclooctane, to a ketone,



**Fig. 3** Proposed mechanism of ruthenium-catalyzed C–H electrooxidation

perform C–H oxidation,<sup>1</sup> generating ruthenium dioxide which migrates back to the aqueous phase. Inorganic chromium salts are also able to oxidize activated (allylic and benzylic) C–H bonds under these electrocatalytic conditions. Both iron- and iridium-based species were unsuccessful in this system.

As synthetic and procedural tractability is a major goal of this project, we also spent part of the reporting period developing a robust and simple electrochemical reactor (Fig. 4). This apparatus is easily-assembled from laboratory materials and was used for the majority of preparative experiments.



**Fig. 4** Left: materials used to assemble electrochemical reactor; Right: assembled electrochemical reactor

**Research plans for year 2:** Our plans for the second year will focus on the continued development of the complementary ruthenium and chromium electrooxidation systems. Of particular interest are the reactivity of each catalyst with hydrocarbon substrates and potential complementarity between these approaches.

We will also continue to look at heterogeneous oxidation catalysts, including the LDH from our initial studies, for achieving hydrocarbon transformations. We will attempt to address the stability barrier in this application via judicious variation of solvent and supporting electrolyte.

**Impact:** The PI (Harry Gray) has been able to leverage this award to initiate ongoing collaborations with the Co-PI (Brian Stoltz) and mentor several junior researchers across both labs. Gray worked with Julian West, a former postdoc who has since begun a tenure-track appointment at Rice University; and with Dana Levine, who is a research scientist at Gilead Pharmaceuticals. This award has allowed the PI to begin a research program based on his expertise in inorganic electrocatalysis that if successful will have an impact on the course of synthetic organic chemistry.