ROADMAPS TO OCEAN WORLDS. A. R. Hendrix[1], T. A. Hurford[2], the ROW Team. [1]Planetary Science Institute, Tucson, AZ (arh@psi.edu), [2]NASA Goddard Space Flight Center, Greenbelt, MD (terry.a.hurford@nasa.gov).

Introduction: The House Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2016 directed NASA to create an Ocean Worlds Exploration Program whose "primary goal is to discover extant life…" To support this initiative, NASA's Outer Planets Assessment Group (OPAG) formed the Roadmaps to Ocean Worlds (ROW) to lay the scientific groundwork for such a program, and as input to the Decadal mid-term review and the next full survey. OPAG gave ROW the following charter:

• Identify and prioritize science objectives for Ocean Worlds (tied to the 2013 Decadal Survey) over the nest several decades

• Design roadmap(s) to explore these worlds to address science objectives (including mission sequences, considering a sustained exploration effort)

• Assess where each Ocean World fits into the overall roadmap

• Summarize broad mission concepts (considering mission dependencies and international cooperation)

• Recommend technology development and detailed mission studies in support of the next decadal survey

The ROW team is producing two documents: 1) Goals, Objectives, Investigations for Ocean Worlds and 2) Ocean Worlds Missions Scenarios, Roadmaps & Technologies; here we highlight the goals and investigations.

Definition of an Ocean World: For the purposes of ROW, and to bound the extent of a future Ocean Worlds program, we define an "ocean world" as a body with a current liquid ocean (not necessarily global). All bodies in our solar system that plausibly can have or are known to have an ocean will be considered as part of this document. The Earth is a well-studied ocean world that can be used as a reference ("ground truth") and point of comparison.

Philosophy and Overarching Goal: There are several – if not many – ocean worlds or candidate ocean worlds in our solar system, targets for future NASA missions in the quest to understand the distribution and origin of life in the solar system. In considering ocean worlds, there are several with confirmed oceans, several candidates that exhibit hints of potential oceans, and worlds that may theoretically harbor oceans but about which not enough is currently known. As a philosophy, the ROW team deems it critical to consider all of these worlds in order to understand the origin and development of oceans and life in different worlds: does life originate and take hold in some ocean worlds and not others and, if so, why? Thus, the ROW team supports the creation of a program that studies the full spectrum of ocean worlds; if only one or two ocean worlds are explored and life is discovered (or not), we won't fully understand the distribution of life, its origin and variability, or the repeatability of its occurrences in the solar system.

We have considered that Enceladus, Europa, Titan, Ganymede and Callisto have known subsurface oceans, as determined from measurements by the Galileo and Cassini spacecraft. These are *confirmed* ocean worlds. Europa and Enceladus stand out as ocean worlds with evidence for communication between the ocean and the surface. Titan, Ganymede and Callisto's subsurface oceans are expected to be covered by a relatively thick ice shell, making exchange processes with the surface more difficult, and with no obvious surface evidence of the oceans.

Although Titan possesses a large subsurface ocean, it also has an abundant supply of a wide range of organic species and surface liquids, which are readily accessible and could harbor more exotic forms of life. Furthermore, Titan may have transient surface liquid water such as impact melt pools and fresh cryovolcanic flows in contact with both solid and liquid surface organics. These environments present unique and important locations for investigating prebiotic chemistry, and potentially, the first steps towards life.

Bodies such as Triton, Pluto, Ceres and Dione are considered to be *candidate* ocean worlds based on hints from limited spacecraft observations. For other bodies, such as some Uranian moons, our knowledge is limited and the presence of an ocean is uncertain but they are deemed *credible possibilities*.

The ROW team decided on an overarching goal for the roadmaps: **Identify ocean worlds, evaluate their habitability, and search for life**. This overarching goal has four underlying sub-goals, described here:

Goal I: Identify ocean worlds in the solar system.

I. A. Is there a sufficient energy source to support a persistent ocean?

A.1 Is there remnant radiogenic heating?
A.2 Is there or has there been significant tidal heating?

I. B. Are signatures of ongoing geologic activity (or current liquids) detected?

B.1 Do signatures of geologic activity indicate the possible presence of a subsurface ocean? (surface hotspots, plumes, crater-free areas, volcanoes, tectonics)
B.2 Does the body exhibit tidal and/or rotational evidence indicating the presence of a sub-surface ocean?
B.3 Does the gravity and topography of the body indicate the presence of a sub-surface ocean?

B.4 Are temporal changes observed at the body that would indicate the presence of a sub-surface ocean?
B.5 Is there an atmosphere or exosphere that could be linked with the presence of a sub-surface ocean?
B.6 Does the electromagnetic response of the body indicate the presence of a sub-surface ocean?
B.7 Can the surface composition be linked with the presence of a sub-surface ocean?
B.8 Is the signature of a surface liquid observed (e.g. specular reflection)?

I. C. How do materials behave under conditions relevant to any particular target body?
C.1 What are the phase relations of materials composing ocean worlds at relevant pressures and temperatures?
C.2 What is the composition and chemical behavior of materials composing ocean worlds?
C.3 What are the rheological mechanisms by which material deforms under conditions relevant to ocean worlds?
C.4 How does energy attenuation/dissipation occur under conditions relevant to ocean worlds?
C.5 What are the thermophysical properties of material under conditions relevant to ocean worlds?

Goal II: Characterize the ocean of each ocean world.
II.A Characterize the physical properties of the ocean and outer ice shell
A.1 What is the thickness, composition, and porosity of the ice shell (crust) and how do these properties vary spatially and /or temporally?

A.2 What is the thickness, salinity, density and composition of the ocean? How do these properties vary spatially and /or temporally?
A.3 What are the drivers for, and pattern of, fluid motion within the ocean.

II. B. Characterize the ocean interfaces
B.1 Characterize the seafloor, including the high-pressure ocean – silicate interaction
B.2 Characterize the ice-ocean interface

Goal III: Characterize the habitability of each ocean world.
III.A. What is the availability (type and magnitude/flux) of energy sources suitable for life, how does it vary throughout the ocean and time, and what processes control that distribution?

A.1 What environments possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes?
A.2 (Where) is electromagnetic radiation available? In what wavelengths and intensity?

III.B. What is the availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?
B.1 What is the inventory of organic compounds, what are their sources and sinks, and what is their stability with respect to the local environment?
B.2 What is the abundance and chemical form of nitrogen, oxygen, phosphorus, sulfur, and inorganic carbon, what are their sources and sinks, and are there processes of irreversible loss or sequestration relative to the liquid environment?

Goal IV: Understand how life might exist at each ocean world and search for life
IV.A. What are the potential biomarkers in each habitable niche? (determine what we're looking for)
A.1 What can we learn about life on ocean worlds from studying life on Earth?
A.2 What niches for life are possible on ocean worlds?
A.3 What can we learn about life by understanding the history of ocean worlds from their formation to the present?
A.4 What should be our target indicators? (Life Detection Ladder)
A.5 How do we distinguish extant from extinct life in environments in which life might develop, and which timescales (e.g., for metabolism, reproduction, dormancy) matter?

IV.B. How to search for and analyze data in different environments?
B.1 How can we look for life on an ocean world remotely (from orbit or during a flyby)?
B.2 How can we look for life on an ocean world in situ (landed, underwater, plume) investigations?
B.3 How can we look for life on an ocean world with sample return science?
B.4 Which science operational strategies should be used to detect life on ocean worlds?

ROW is focused on the search for signs of extant life and characterizing the potential habitability of ocean worlds. The goals outlined here offer a vision of ocean world-related planetary science beginning over the next 3 decades. Key to accomplishing these goals are technological advances, for instance *in situ* life detection and sampling methods, power sources and energy storage systems suitable for cryogenic environments, autonomous systems for e.g. pin-point landing on Titan (different from Europa and Enceladus) and aerial or landed mobility, subsurface ice acquisition/handling, plume capture, planetary protection technologies and ice sample return with cryogenic preservation. Technologies also need to be developed for survival and operation of both electronic and mechanical systems in the ocean world environments.