III.B.1 Innovative Hydrogen Liquefaction Cycle

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Subcontractors:
- R&D Dynamics, Bloomfield, CT
- Massachusetts Institute of Technology, Cambridge, MA

Start Date: August 1, 2005
Project End Date: August 1, 2009

Objectives

Reduce the cost and improve the energy efficiency of hydrogen liquefaction.

- Develop and model a large capacity (50,000 kg/day or greater) hydrogen liquefaction cycle that:
  - Attains efficiencies which are a 33% improvement over present state-of-the-art systems.
  - Reduce the capital expense relative to similar capacity systems.
- Develop efficient turbo-machinery for the H_2 liquefaction cycle.
- Produce a small-scale (~500 kg/day) hardware demonstration of a hydrogen liquefaction plant to cost effectively demonstrate the large capacity system design and architecture.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section (3.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(C) High Cost and Low Energy Efficiency of Hydrogen Liquefaction

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Project Overview

The purpose of this project is to produce a pilot scale liquefaction plant that demonstrates Gas Equipment Engineering Corp.'s ability to meet or exceed the efficiency targets set by the Department of Energy. This plant will be used as a model to commercialize this technology for use in the distribution infrastructure of hydrogen fuel. It could also be applied to markets distributing hydrogen for industrial gas applications.

This project will design and build a small-scale pilot plant (several hundred kg/day) that will be both a hardware demonstration and a model for scaling to larger plant sizes (>50,000 kg/day). A key component that will be developed in this project is an efficient foil-bearing turbo-expander to perform the cycles cryogenic cooling. The major challenge of the project is to optimize/balance the performance (efficiency) of the plant against the cost of the plant so that the fully amortized cost of liquefying hydrogen meets the aggressive goals set by DOE.

Accomplishment Summary

1. A new project team was assembled and subcontracts put into place.
2. Accurate state properties for hydrogen at cryogenic temperatures and elevated pressures were identified.
3. A simple cycle model (using Excel) was assembled to allow evaluation of various cycles and component configurations.
4. The result of the cycle evaluation and modeling, and discussion with the turbo-expander development partner, R&D Dynamics, resulted in the selection of a cycle with the following characteristics:
   - Indirect cooling of the hydrogen stream via heat exchangers.
   - An independent cooling cycle using turbo-expanders.
   - A "once through" hydrogen liquefaction stream at slightly elevated pressures that is reduced to atmospheric pressure by a hydraulic expander.

Preliminary modeling shows that this cycle has the potential to achieve over 40% of Carnot efficiency – a 30% increase over existing cycles.

Over the coming quarter this basic cycle will be evaluated at several pressure and flow conditions so that performance estimates at various outputs (500 kg/day, 5,000 kg/day, and 50,000 kg/day) can be evaluated and individual component cost and performance can be estimated. A final cycle design for the 500 kg/day pilot plant and 50,000 kg/day full-scale plant design will be selected. The project will then move to detailed design and component selection, and economic capital and operating assessment that will be presented at the go/no-go project review in December 2007.

Background

The simplest liquefaction process is the Joule Thomson expansion cycle (Figure 1). The gas to be liquefied is compressed, cooled in an after-cooler, and then undergoes isenthalpic expansion across a throttle valve. If the gas is cooled below its inversion temperature in a heat exchanger, then this expansion results in further cooling and may result in liquid formation at the valve outlet. For hydrogen, this temperature is -95ºF. It is obvious that this cycle alone cannot be used for liquefaction of hydrogen without any pre-cooling of hydrogen below its inversion temperature. A modification of this cycle is sometimes used in which liquid nitrogen is used to cool the gaseous hydrogen below its inversion temperature and then Joule Thomson expansion is used to liquefy hydrogen.

Joule Thomson expansion is inherently inefficient as there is no work done during expansion. The industrial gas industry departed from using Joule Thomson as a primary process used in liquefaction of atmospheric gases in the 1960s. Turbo-expanders or expansion engines are now used at most industrial gas plants to provide the necessary refrigeration for liquefaction. The expansion across a turbo-expander is ideally isentropic, or in other words, some useful work is done in expansion. But turbo-expanders cannot tolerate any liquid condensing at the outlet as the turbine wheels often rotate at speeds exceeding 100,000 rpm. Therefore, a clever combination of isentropic and isenthalpic expansion is required to generate a practical efficient process when the expansion process is applied directly on the hydrogen gas stream. Figure 2 shows a schematic for the simplest version of a combined reverse Brayton and Joule Thompson (CRBJT) hydrogen liquefaction cycle. This is similar to the cycles used in state-of-the-art hydrogen liquefiers.

Changes to the Originally Planned Cycle Approach

We originally proposed to use an optimized combination of the reverse Brayton expansion cycle (or a modified Claude cycle) with the Joule Thompson expansion cycle. At the beginning of the project the scope was expanded to look at a broader range of alternate cycles. We are working with the Massachusetts Institute of Technology (MIT) Cryogenics Laboratory to select the cycles to be evaluated and modeled.

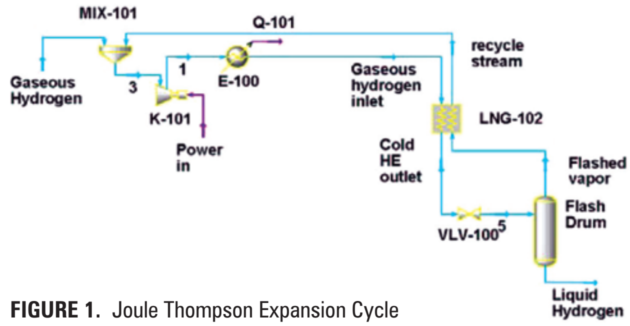

FIGURE 1. Joule Thompson Expansion Cycle

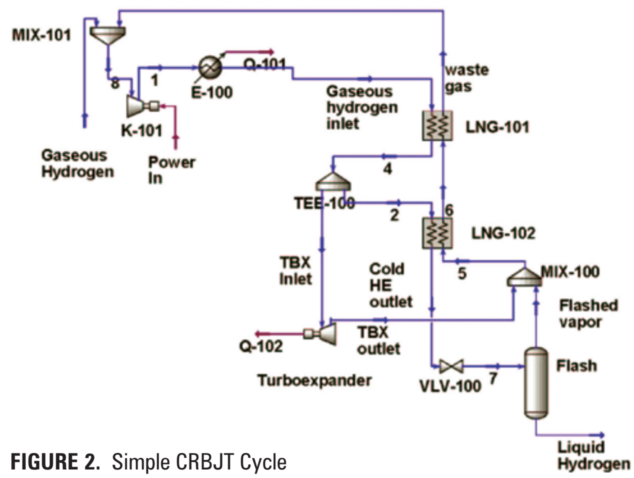

FIGURE 2. Simple CRBJT Cycle

Task Schedule and Progress Summary

Task Number	Project Milestones	Task Completion Date		
		Original Planned	Revised Planned	Percent Complete
1	Design Cycle/Identify Major Components	12/31/05	07/31/07	80%
2	Detailed Design	7/31/06	12/30/07	10%
3	Design and Build Turbo Expanders	12/31/06	6/31/08	0%
4	Procure Major Components	12/31/06	6/31/08	0%
5	Build Plant	9/30/07	12/31/08	0%
6	Test Plant	6/31/08	9/30/09	0%

Project Milestones

Year One Funding

- Project Kickoff Meeting – Beginning of Task 1 – Complete
- Preliminary Design Complete – End of Task 1 – Substantially Complete
- Detailed Design Complete – End of Task 2 – Initiated

Year Two Funding

- Turbo-Expander Complete – End of Task 3
- Test Plan Review Meeting – End of Task 4

Year Three Funding

- Plant Fabrication Complete – End of Task 5
- Testing Complete – End of Task 6 and Project

Progress During the Previous Year (4/1/06 to 3/31/07)

Significant progress was made in evaluating and selecting a hydrogen liquefaction cycle during the 2nd quarter FY 2007 period (1/1/07 to 3/31/07). Highlights of the progress are as follows:

1. A formal subcontract was negotiated with MIT, including the handling of proprietary or patentable concepts coming from the collaborative GEECO/MIT effort.
2. A kick-off meeting with MIT and GEECO was held.
3. Appropriate hydrogen properties and useful (reasonably accurate) equations of state were identified of previous equations of state for the combination of pressure, temperature, and para/ortho state.
4. An Excel-based modeling program was written to allow parametric evaluation of the various cycles in a quick, but accurate methodology.
5. Preliminary results of the modeling and discussion with R&D Dynamics led the team to select indirect cooling of the hydrogen stream using either helium, helium/neon, or nitrogen cooling loops (reverse Brayton cycles), due to the following:
   - The very high risk and potential cost of developing a hydrogen turbo-expander for the low temperature cycle conditions.
   - The desire to produce a "once-through" hydrogen cooling cycle that can significantly reduce the size of both the cooling and heat exchange components.
6. The initial results were presented at a Delivery Team Review Meeting on February 17, 2007 in Washington, D.C.
7. Further evaluation resulted in the selection of a "once-through" hydrogen cycle at elevated pressure that avoids passing through the two phase vapor dome during cooling, thus avoiding all twp phase flow complications in the heat exchangers.
8. A hydraulic motor was selected as the means for reducing the pressure of the cooled hydrogen stream and liquefying the entire "once-through" flow rate.
9. Further evaluation and modeling resulted in a baseline design for the cycle that yields a significant increase in efficiency over the current state-of-the-art cycles used by commercial entities.
10. Turbo-expander flow and pressure parameters were sent to R&D Dynamics so that an initial estimate of component feasibility could be made.

Results

This basic cycle is shown in Figure 3. Preliminary modeling shows that this cycle has the potential to achieve over 40% of Carnot efficiency – a 30% increase over existing cycles.

Figure 4 shows the results of the modeling for one of the characteristic cycles at various process stream pressures and turbo-expander pressure ratios, and heat exchanger efficiencies. The realistic assumptions for component performance used in these models supports the conclusion that significant efficiency increases are possible with this cycle approach.

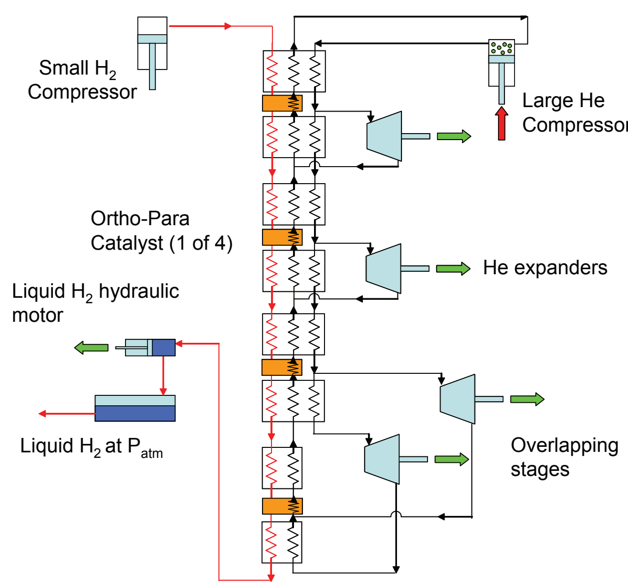

FIGURE 3. Basic Cycle Definition

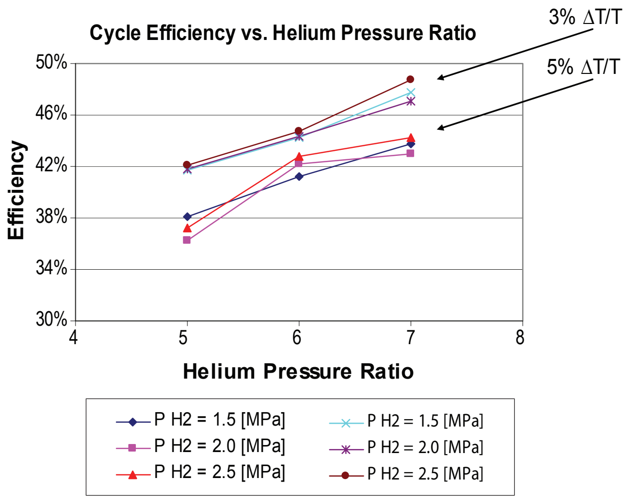

FIGURE 4. Basic Cycle Modeling Results

Future Work

Over the next six months we will work iteratively with our subcontractors, evaluating turbo-expander design (expected performance and development risk/cost) and heat exchanger and catalyst bed cost and performance against overall cycle design. Several variations in the basic cycle design such as nitrogen cooling of the warmer stages and using specific component performance estimates for individual components will be performed. In addition, MIT will perform an overall performance sensitivity study to component efficiency at the various cycle stages so that we may fine tune (i.e. understand the cost trade-off) the final cycle hardware cost relative to the overall cycle efficiency. We will evaluate the cycle performance estimates at various outputs (500 kg/day, 5,000 kg/day, and 50,000 kg/day) and estimate individual component cost. A final cycle design for the 500 kg/day pilot plant will be selected that allows us to cost effectively demonstrate the expected performance of a 50,000 kg/day full-scale plant design. The project will move detailed design and component selection, along with economic capital and operating cost assessment to be presented at the go/no-go project review in December 2007.