H2A Delivery Components Model Version 1.1: Users Guide

April 7, 2006

Definition of Hydrogen Delivery

Hydrogen delivery is an essential component of any future hydrogen energy infrastructure. Hydrogen must be transported from the point of production to the point of use, and handled within refueling stations or stationary power facilities. The scope of hydrogen delivery includes everything between the production unit (central or distributed) and the onboard fueling tank on a fuel-cell vehicle.

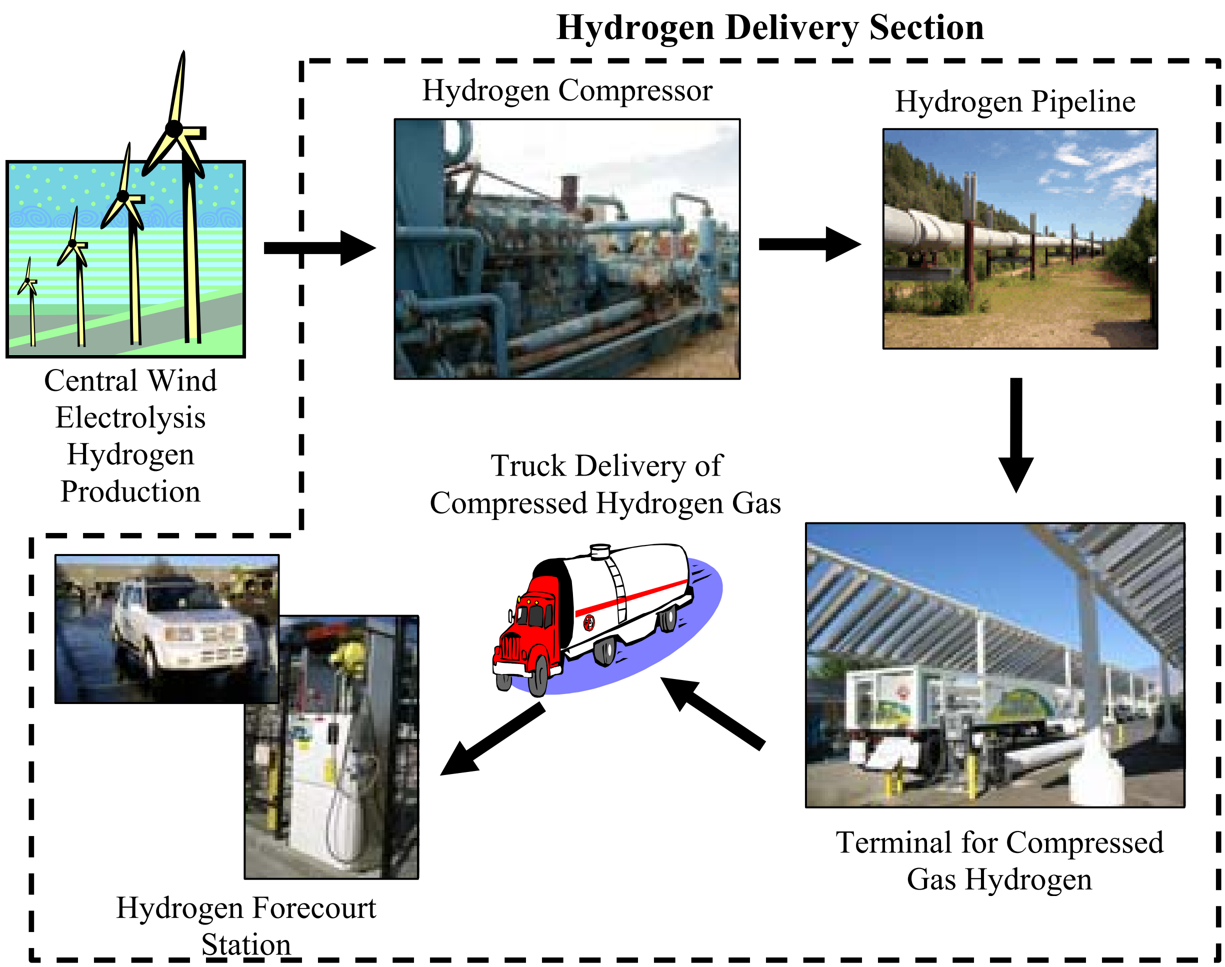

Figure 1. Potential Hydrogen Delivery Infrastructure

In the hypothetical example shown in Figure 1, the hydrogen is produced through a wind electrolysis system. Then, the hydrogen is compressed up to pipeline pressure, and then fed into a transmission pipeline. The pipeline delivers hydrogen to the compressed gas terminal, where the hydrogen is loaded into compressed gas tube trailers. A truck delivers the tube trailers to forecourt station so that the hydrogen can be dispensed into fuel cell vehicles. The delivery portion of the hydrogen supply chain is enclosed in the dashed area.

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1.0 The H2A Delivery Component Model

The H2A Delivery Component model is one of two models that have been developed by the H2A Delivery Team. The model focuses on components that will be required to deliver liquid hydrogen or compressed hydrogen gas from a central production plant to a forecourt station and then onto the onboard fueling tank of a fuel cell vehicle. At this point, novel storage and delivery technologies, such as metal hydrides and alanates, are not modeled. The components that are modeled in the tool are listed below.

Delivery Components
- Truck – hydrogen gas tube trailer, 2700 psi
- Truck – hydrogen gas tube trailer, 7000 psi
- Truck – liquid hydrogen tank
- Pipeline
- Liquefier
- Compressor (single- or multi-stage units)

Storage Components
- Compressed gas tubes
- Bulk liquid tanks
- Geologic/underground

Delivery/Storage Components
- Compressed hydrogen gas terminal
- Liquid hydrogen terminal

Forecourt Components
- Forecourt compressor
- Forecourt dispenser
- Forecourt storage

Integrated Forecourt
- Forecourt station – compressed hydrogen gas delivery
- Forecourt station – liquid hydrogen delivery

The tool is based in Microsoft's Excel spreadsheet program. The overall spreadsheet includes the 24 tabs. Each of the components introduced above has a separate tab which contains tables and descriptions to guide users how to enter data. Some of the tabs contain only data, and are locked to prevent formulas from being accidentally deleted or changed. Each tab is identified and described in the list below.

- Title: The user enters information such as their name, phone number and email address.
- Forecourt Station – Gaseous H2: The hydrogen cost contribution from a forecourt station supplied with gaseous hydrogen can be determined using this tab. This tab is designed based on the Forecourt Compressor, Forecourt Dispenser and Forecourt Storage tabs.

- Forecourt Station – Liquid H2: This tab can be used to determine the cost contribution of a forecourt station which is fed with liquid hydrogen. The hydrogen is still dispensed as a gas.
- Forecourt Compressor: This tab is used to calculate the hydrogen cost contribution of a forecourt compressor.
- Forecourt Dispenser: The hydrogen cost contribution of either a single dispenser or multiple dispensers can be calculated with this tab.
- Forecourt Storage: This tab allows the user to calculate the hydrogen cost contribution associated with compressed gas storage at a Forecourt station.
- Truck-Tube Trailer Delivery_2700 psi: The portion of the delivered hydrogen cost contribution attributed to delivery using a truck and compressed gas tube-trailer (current technology with maximum pressure of approximately 2700 psig) can be calculated using this tab.
- Truck-Tube Trailer Delivery_7000 psi: The portion of the delivered hydrogen cost contribution attributed to delivery using a truck and compressed gas tube-trailer (future technology with maximum pressure of 7000 psig) can be calculated using this tab.
- Compressed Gas H2 Terminal: The hydrogen cost contribution of a compressed hydrogen gas terminal can be calculated using this tab. This tab is designed based on the H2 Compressor tab, and the Compressed Gas H2 Storage Tube tabs.
- Compressed Gas H2 Storage Tubes: Large-scale compressed hydrogen gas storage is modeled and costed based on the inputs to this tab.
- Truck-LH2 Delivery: This tab is used to calculate the cost contribution to the delivered hydrogen cost from liquid hydrogen delivery by truck and insulated trailer.
- Liquid H2 Terminal: This tab is used to calculate the cost contribution to the delivered hydrogen cost from a liquid hydrogen terminal.
- H2 Liquefier: The hydrogen cost contribution of a hydrogen liquefier can be calculated using this tab.
- Bulk Liquid Hydrogen Storage: Large-scale liquid hydrogen storage is designed and costed using this tab.
- H2 Compressor: The hydrogen cost contribution of a large single or multi-stage compressor can be calculated using this tab.
- H2 Pipeline: The portion of the delivered hydrogen cost that can be attributed to a hydrogen pipeline infrastructure can be calculated using this tab.
- Geologic Storage: The hydrogen cost contribution of a geologic storage cavern can be calculated using this tab.
- Feedstock & Utility Prices: This tab contains feedstock projections, through 2070, for a variety of potential feedstocks and utilities. The information presented in this tab was developed for the overall H2A effort, and is included in both the H2A Central Production model and the Forecourt Production Model. This tab is locked to prevent the user from accidentally changing any of the values.
- Physical Property Data: The values in this tab show physical property data for various feedstocks and utilities, as well as environmental data. The database used in the Greenhouse Gas, Regulated Emissions and Energy Use in Transportation (GREET) model, developed by Michael Wang at Argonne National Laboratory, was used to

develop the information included in this tab. The values on this tab cannot be changed by the user.

- MACRS_Dep. Table: The depreciation calculations for each of the components are performed in this tab. The values on this tab cannot be changed by users.
- Liquefier Cost_Efficiency: This tab contains the data and corresponding graphs that were used to determine the H2A base case liquefier capital cost estimate. Additionally, the tab also includes data on liquefier efficiency versus liquefier size. The data on this tab is locked.
- Liquid Storage Costs: This tab contains data used in developing H2A base case capital cost estimates for liquid hydrogen storage. The values on this tab cannot be changed.
- Pipeline Costs – OGJ: To develop a capital cost approximation for pipelines, the H2A Delivery team used results compiled for natural gas pipeline costs by Nathan Parker of the University of California at Davis. His work was based on data published in the Oil and Gas Journal in an annual article on pipeline economics. This tab contains the data and resulting graphs that were used to develop the estimates. The data in this tab cannot be changed.
- Large Compressor Costs: This tab shows the data, taken from the Oil and Gas Journal, used in capital cost estimates for large scale hydrogen compressors. The data on this tab is locked.

1.1 Example Cases

The Hydrogen Delivery Components model comes pre-loaded with data for each tab. The data for each component is meant to represent the H2A Delivery Team's best understanding of currently available technology and costs. The pre-loaded cases are not meant to represent the final cost for any hydrogen delivery component.

1.2 References for Data

When necessary, particular entries within the Hydrogen Delivery Components model are referenced to the source where they were obtained. A full citation is included in the "Reference" cell next to the entered data point. A full citation for data used in this manual is provided in the References section at the end of this manual.

1.3 Color Coding in the H2A Delivery Components Model

The cells in each tab of the H2A modeling tool are color coded to show the user how the values entered are used in the tool. The color-coding convention is shown below.

COLOR CODING

(blue)	**= Calculated Cells (do not change formulas)**
(orange)	**= Input Required; Input Used in Economic Calculations**
(green)	**= Optional Input; Input NOT Used in Economic Calculations**
(yellow)	**= Information Cells**

The blue cells in the model are locked. When scrolling through the various tabs, you can select a blue cell to see how the calculation is completed, but you will not be able to change the formulas.

The orange cells represent required user inputs. As will be discussed later, the omission of a value in an orange cell will activate the error detection system within the model that will help the user identify where there is required input missing or an incorrect value is used.

The light green cells are typically used for comment and reference cells. The information entered in these cells is beneficial to future users of the model, as it can help them pinpoint the reason a particular input was used.

The yellow cells are always on the right hand side of the tables, and provide useful information to the user. For example, the information in the yellow cells may guide the user as to what appropriate values for a particular cell might be.

Figure 1 shows a table taken from the Truck-Tube Trailer Delivery tab. It shows how the colors are used in the model. All the values in the Base Case column, except for the reference year dollars and the total tax rate, are orange and thus require user inputs. The H2A Base Case column is shaded yellow because the values are for informational purposes. The green cells contain comments and the data source. The addition of comments helps to identify why a particular value was used. Finally, the blue cells contain formulas (as in the total tax rate) or a fixed value (such as the reference year dollars) and cannot be changed by the user.

Economic Assumptions

	Base Case	H2A Base Case	Comments	Data source
Assumed start-up year	2005	2005		H2A
Reference year dollars	2005	2005	All base case H2A analyses are in year 2005 dollars	H2A
Real After-tax Discount Rate (%)	10.0%	10%	This discount rate is used throughout the H2A analyses	H2A
Tractor MACRS Depreciation Schedule Length (years)	5	5	Taken from IRS Publication 946, Table B-2, Asset Class 00.242	IRS
Trailer MACRS Depreciation Schedule Length (years)	5	5	Taken from IRS Publication 946, Table B-2,Asset Class 00.27	IRS
Tractor Lifetime (years)	5	5		KIC
Trailer Lifetime (years)	20	20		KIC
Analysis period (years)	20	20	This is the base analysis period of H2A cases.	H2A
Inflation Rate (%)	1.9%	1.9%	Reference inflation for H2A cases is 1.9% per year	H2A
State Taxes (%)	6.0%	6%		H2A
Federal Taxes (%)	35.0%	35%	Corporate Tax Bracket - H2A standard	H2A
Total Tax Rate (%)	38.9%			

Figure 2. Color-Coding in the H2A Delivery Components Model

1.4 Layout of the Delivery Component Tabs

Each of the 16 component tabs is arranged in a similar manner. The first item that a user will see at the top of each tab is the title, a brief description of the calculations (some tabs do not contain a description) and the color-coding table. The next item that a user will see is a blue table, entitled Calculation Outputs. This table will contain the final cost and energy efficiency results based on the values entered in the component tab by the user. The top row of the Calculation Outputs table will always show the final hydrogen cost contribution for each component. The rows immediately below the final hydrogen cost will break the price into individual components, such as for capital and for operation and maintenance. The details of the financial analysis calculations will be described in a later section.

Mass and energy efficiency information will be shown directly below the cost results. The calculations for energy efficiency will be described in a later section. The final entry in the Calculation Outputs table will always be the After-Tax IRR that was used in the economic calculations.

Figure 3 shows the top section of the H2 Compressor page.

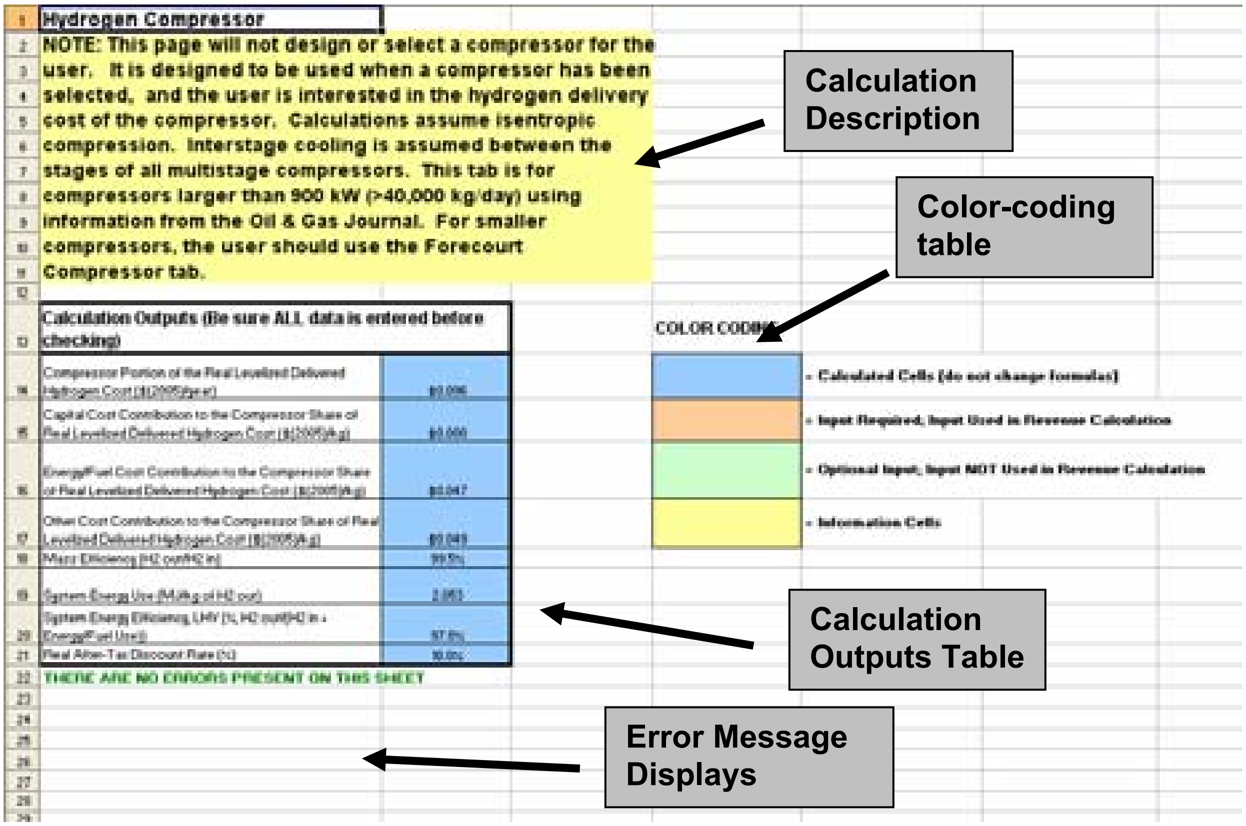


Figure 3. Top Portion of Delivery Component Model Tabs

Directly below the Calculation Outputs table is where the results from the error detection system are displayed. If there are no errors in the model, a message will appear right below the Calculations Outputs column that, in green letters, says "There are not errors present on this sheet". This comment is visible in Figure 3. If errors are present, the green "no errors" statement will disappear, and red lettered messages will show up directly below where the original green message was displayed. These red messages will direct the user to the part of the particular component tab where an error has been detected. To find the error, go to the section described, and look for a red error message in the cells directly to the right of the particular table.

The next table in each tab allows the user to enter specific design parameters for the particular components. Figure 4 shows an example of the design parameter input table for the Truck-Tube Trailer Delivery tab. The explanations in the first column tell the user what information is to be entered in each cell. For example, one row asks for the maximum operating pressure of the tubes while another asks for the minimum pressure in the same tubes. The cells in column 2 are shaded orange, which means that user input is required. The third and fourth columns are where the user can input comments and list the source for the information. These cells are shaded green, meaning that they are optional inputs. For the number of tubes, the comment reads "super jumbo trailer holds 9 tubes" with a data source of "Weldship Super Jumbo Tube Trailer Specification Sheet. Obtained from http://www.weldship.com/weld_pdf/superjumbo.pdf". In the far right column, which is shaded yellow for information cells, guidance is provided for the user. For example, the top information cell reads "Please use the pull-down menu to the right of the value cell to enter ***yes*** or ***no***. If ***no*** is selected, input is required in B29.” Comments such as this are used throughout the model to guide the user about the types of entry required.

21	*Truck-Tube Trailer Design Inputs*				
22	**Design Input**	**Value**	**Comments**	**Data Source**	**Information**
23	Calculate Truck Capacity Based on Tube Water Volume and Pressures?	yes			Please use the pull-down menu to the right of the value cell to enter yes or no. If "no" is selected, input is required in B29.
24	Tube Maximum Operating Pressure (atm)	180	2640 PSIG	Weldship Super Jumbo Tube Trailer Specification Sheet. Obtained from http://www.weldship.com/weld_pdfs/superjumbo.pdf	
25	Tube Minimum Pressure (atm)	15	Assumption that tank can never be "completely" emptied. 15 atm corresponds to 220 psig	H2A	
26	Number of Tubes	9	Super Jumbo trailer holds 9 tubes	Weldship Super Jumbo Tube Trailer Specification Sheet. Obtained from http://www.weldship.com/weld_pdfs/superjumbo.pdf	
27	Tube Water Volume (m3)	2.4	Converted from 85.8 ft3 of water volume	Weldship Super Jumbo Tube Trailer Specification Sheet. Obtained from http://www.weldship.com/weld_pdfs/superjumbo.pdf	
28	Tube Operating Temperature (degrees C)	25		H2A	
29					Input only required if B23 = "No"

Figure 4. Sample Design Inputs Table.

After the design inputs table, the user is then asked to enter information about various scenario inputs, such as delivery distance (truck tabs) or hydrogen lost during delivery. The scenario table looks very similar to the design inputs table, with orange input cells, green comment and data source cells, and yellow information cells. It is important to note that not all tabs have a scenario inputs table! Some move directly to the calculations table.

The calculations table is shaded entirely blue, meaning that no user input is required. A sample calculation table from the H2 Compressor tab is shown in Figure 5. Most of the calculation tabs determine the amount of hydrogen actually delivered by a particular component. Additionally, power requirements are determined using inputs from the design and scenario sections.

55	*Compressor Calculations*	
56	**Item**	**Value**
57	Gas Constant (kJ/K.kg-mol)	8.3144
58	Mean Compressibility Factor	1.02797
59	Pressure Ratio	1.7
60	Number of Stages	3.0
61	Net Hydrogen Delivered (kg/year)	182,500,000
62	Design Flowrate to Each Compressor (kg/day)	359,296
63	Theoretical Power Requirement (kW)	6,831

Figure 5. Sample Calculations Table

After the calculations table, each tab includes an economic table. This table, shown in Figure 6, looks almost exactly the same for each component. The user enters information such as plant life, and tax rate in this table. The values entered are used in the fixed-charge rate financial calculations at the bottom of each tab.

69	*Economic Assumptions*				
70		**Base Case**	**H2A Base Case**	**Comments**	**Data source**
71	Assumed start-up year	2005	2005	This start-up year represents a near term case	H2A
72	Reference year dollars	2005	2005	As a base case, all H2A analyses are based on year 2005 dollars	H2A
73	Real After-tax Discount Rate (%)	10.0%	10%	This discount rate is used throughout the H2A analyses	H2A
74	MACRS Depreciation Schedule Length (years)	15	15	Taken from IRS Publication 946,Table B-2, Asset Class 46.0	IRS
75	H2 Pipeline Lifetime (years)	20	20		H2A
76	Analysis period (years)	20	20	This is the base analysis period of H2A cases	H2A
77	Inflation Rate (%)	1.9%	1.9%	Reference inflation rate for H2A is 1.9%	H2A
78	State Taxes (%)	6.0%	6%		H2A
79	Federal Taxes (%)	35.0%	35%	Corporate Tax Bracket - H2A standard	H2A
80	Total Tax Rate (%)	38.9%			

Figure 6. Sample Economic Assumptions Tab.

The next two tables in each tab handle the capital and other costs. The capital investment table guides the user as to what costs need to be entered. Since the H2A Delivery team has provided cost curves for some of the components, the user will be asked whether or not they want to use H2A capital costs, or if they want to enter their own costs. This feature increases the flexibility of the model. The capital investment section, although laid out in a similar fashion, tends to look slightly different for each tab.

The other costs table is located directly below the capital investment table. The number of entries required in this table will depend on whether or not the user opted to use the H2A capital cost curves, which in some cases include installation costs. If entries are required, the user will need to enter data for items such as land requirements and costs, site preparation costs and engineering fees and project contingencies.

The final table prior to the calculation of the component hydrogen cost contribution is for entry of Operation and Maintenance (O&M) costs. A sample of this table, taken from the Liquefier tab, is shown on the next page. The primary items to be entered include labor requirements and costs, utility or feedstock requirements, insurance costs and property taxes. The O&M table contains both input (orange) and calculation (blue) cells, so the user needs to make sure that they are entering data in the proper location. All of the costs are totaled, and the yearly O&M costs are passed to the economic calculation table for inclusion in the final component hydrogen cost contribution.

An important part of the O&M table is the entry of feedstock or utility cost. The H2A team developed a feedstock cost table that includes projections to 2070. The user can either select to use this data, or input other values. The selection of which option is desired is facilitated using a yes/no toggle switch.

		Cost	Comments	Data source	Information
110	*O&M Costs (Monetary Inputs REQUIRED in Year 2005 $)*				
111		**Cost**	**Comments**	**Data source**	**Information**
112	***Labor Cost***				
113	Labor required (hrs/year)	17,520	Assuming 2 full-time operators (i.e. 2 people on duty)		
114	Labor cost ($(2005)/man-hr)	$24.20	Petroleum Plant Operator	Bureau of Labor Statistics - http://www.bls.gov/oes/2002/naics4_325100.htm#b51-0000	
115	**TOTAL LABOR COST ($(2005)/year)**	$423,984			
116					
117	***Utility Costs***				
118	Electricity Consumption (kWh)	131,960,117			
119	Use the H2A Commercial Electricity Cost Projection?	yes			
120	Electricity Cost ($(2005)/kWh)	$0.08			
121					**Only enter a value here if no is selected in cell E119!**
122	**Total Electricity Cost ($(2005)/year)**	$10,069,797			
123					
124	Insurance (% of Total Capital Investment)	1.0%	2.5% total for property tax and insurance for H2A plants. Split into 1% for insurance and 1.5% for property taxes	H2A	
125	Insurance ($(2005)/year)	$885,106			
126	Property Taxes (% of Total Capital Investment)	1.5%	2.5% total for property tax and insurance for H2A plants. Split into 1% for insurance and 1.5% for property taxes	H2A	
127	Property Taxes ($(2005)/year)	$1,327,659			
128	Licensing and Permits (% of Total Capital Investment)	1.0%	Engineering estimation	H2A Delivery Team	
129	Licensing and permits ($(2005)/year)	$885,106			
130	Operating, Maintenance and Repairs (% of Total Capital Investment)	0.5%	Engineering estimation	H2A Delivery Team	
131	Operating, Maintenance and Repairs ($(2005)/year)	$442,553			
132	Overhead and G&A (% of Total Labor Cost)	50.0%	Engineering estimation	H2A Delivery Team	
133	Overhead and G&A ($(2005)/year)	$211,992			
134	Other Fixed Operating Costs ($(2005)/year)				
135	**TOTAL OTHER FIXED COSTS ($(2005)/year)**	$3,752,416			
136					
137	***TOTAL O&M COSTS ($(2005)/year)***	$14,246,197			

Figure 7. Sample O&M Calculation Table.

The final tables in each tab deal with the calculation of the component hydrogen cost contribution. The actual calculations performed in each of these tables are described in a later section. The hydrogen cost contribution that is calculated in the final row of the Calculations table is fed to the table at the top of the spreadsheet. If necessary, the replacement capital table is used to determine the costs of various component replacements when the component lifetime is less than the analysis period. A sample calculation table is shown in Figure 8.

146	***Cost Calculations***	
147	**Costs Item**	**Value**
148	After-tax Real Discount Rate (%)	10.0%
149		
150	*Fixed Charge Rate Calculation*	
151	After-Tax Real Capital Recovery Factor	0.117
152	Real Present Value of Depreciation	0.851
153	Real Fixed Charge Rate	0.129
154		
155	Total Present Value of Installed Compressor Capital Investment (Year 2005 $)	$47,676,227
156	Total Compressor Energy Cost ($(2005)/year)	$4,258,589
157	Total Compressor Labor Cost ($(2005)/year)	$42,108
158	Total Other O&M Costs ($(2005)/year)	$794,684
159	Required Compressor Revenues ($(2005)/year)	$11,228,120
160	Compressor Real Levelized Delivered Hydrogen Cost (Year 2005 $/kg)	$0.137

Figure 8. Sample Cost Calculations Table.

2.0 H2A Delivery Component Model Operation

The model is designed to be extremely user-friendly, allowing a new user to quickly determine how to operate the tool. To start the model, use the following steps:

1) There are macros contained within the H2A Delivery Components model. Therefore, make sure that the Excel Macro security is set to a Medium or Low (you can access the macro security using the Tools → Macros → Security menu tree).
2) Open the model (ComponentsModel_v2.xls)
3) If your macro security is set to Medium, and dialog box will appear asking the user whether then want to enable macros. Click the button that says "Enable Macros".
4) Each tab is labled. Go to the tab that analyzes the component that you are curious about.
5) Fill out the required data.
6) The model will calculate the cost of the particular component (in $/kg of hydrogen) based on the user data.
7) Please remember that the model will recalculate whenever an input is changed. Therefore, make sure that you think about each change you are making, and how it may affect other variables, before examining the $/kg of hydrogen result.

3.0 H2A Component Model Financial Analysis

The cost contribution for each hydrogen delivery component is calculated using the fixed charge rate financial analysis methodology. In the calculations, it is assumed that all investments are equity-financed (there is no option for debt-financing). In the other H2A cost analysis models, a rigorous discounted cash flow/internal rate of return analysis is used to calculate the hydrogen cost. The goal of the Delivery Component model was to develop a simple tool which could quickly determine the contribution to the final delivered hydrogen cost of a particular component. Therefore, the more simplified fixed charge rate analysis was selected.

IMPORTANT NOTE: In the economic assumptions table for each tab, the user is asked to enter a Real After-Tax Discount Rate. This discount rate is assumed to be equivalent to the Internal Rate of Return, which is used in the H2A Production models. The real after-tax discount rate terminology is used throughout this manual.

Fixed charge rate (FCR) methodology determines the amount of annual revenue needed to cover investments (Short *et al*, 1995). In mathematical terms, the FCR is defined as the amount of revenue per dollar of investment that must be earned each year in order to cover the carrying charges (i.e. return on equity and book depreciation) on that particular investment (Short *et al*, 1995).

The equation for the fixed charge rate is shown below (Short *et al*, 1995).

$$FCR = \frac{UCRF[1-(b)(T)\sum_{n=1}^{M}\frac{V_n}{(1+d_n)^n} - t_c]}{1-T} + p_1 + p_2$$

Where:

FCR = fixed charge rate
$UCRF$ = uniform capital recovery factor, which is defined as:

$$UCRF = \frac{1}{\sum_{n=1}^{N}\frac{1}{(1+d)^n}} = \frac{d(1+d)^n}{(1+d)^n - 1}$$

M = depreciation period (years)
b = fraction of depreciable base (depreciable fraction of capital costs)
n = analysis year
T = total tax rate which is defined as:

$$T = t_f + t_s(1-t_f)$$

t_f = federal tax rate
t_s = state tax rate

V_n = fraction of depreciable base that must be depreciated in year n
d = after-tax discount rate
N = analysis period
t_c = tax credit

p_1 = annual insurance cost as a percentage of total plant investment
p_2 = other taxes paid annually.

In the fixed charge rate analysis used in the Delivery Component model, no tax credits are assumed, and the entire capital investment is assumed to be depreciable. Additionally, insurance costs and other taxes are handled separately. Therefore, the FCR equation reduces to the following.

$$FCR = \frac{UCRF[1 - T\sum_{n=1}^{M}\frac{V_n}{(1+d_n)^n}]}{1-T}$$

The Modified Accelerated Cost Recovery System (MACRS) is used for depreciating the investment for each delivery component. The depreciation tab, described later in this manual, contains the MACRS depreciation schedule for 3, 5, 7, 10, 15 and 20 years. When taken separately, the following portion of the FCR equation:

$$\sum_{n=1}^{M}\frac{V_n}{(1+d_n)^n}$$

is equivalent to taking the present value of each of the MACRS depreciation amounts. Thus, the FCR equation becomes:

$$FCR = \frac{UCRF[1 - T(PV(depreciation))]}{1-T}$$

This equation is used in the model to calculate the fixed charge rate.

To calculate the amount, in \$/kg of hydrogen, that a particular component contributes to the final delivered hydrogen cost, the FCR is multiplied by the present value of the capital investment (including allowances for replacement capital) and added to the operating and maintenance (O&M) expenses. The result of this calculation is then divided by the amount of hydrogen processed by the particular delivery component to give the hydrogen cost contribution in \$/kg of hydrogen.

The following tables were pulled directly from the compressor tab in the Delivery Components model, and will be used as an example of the financial analysis used in the model.

Economic Assumptions

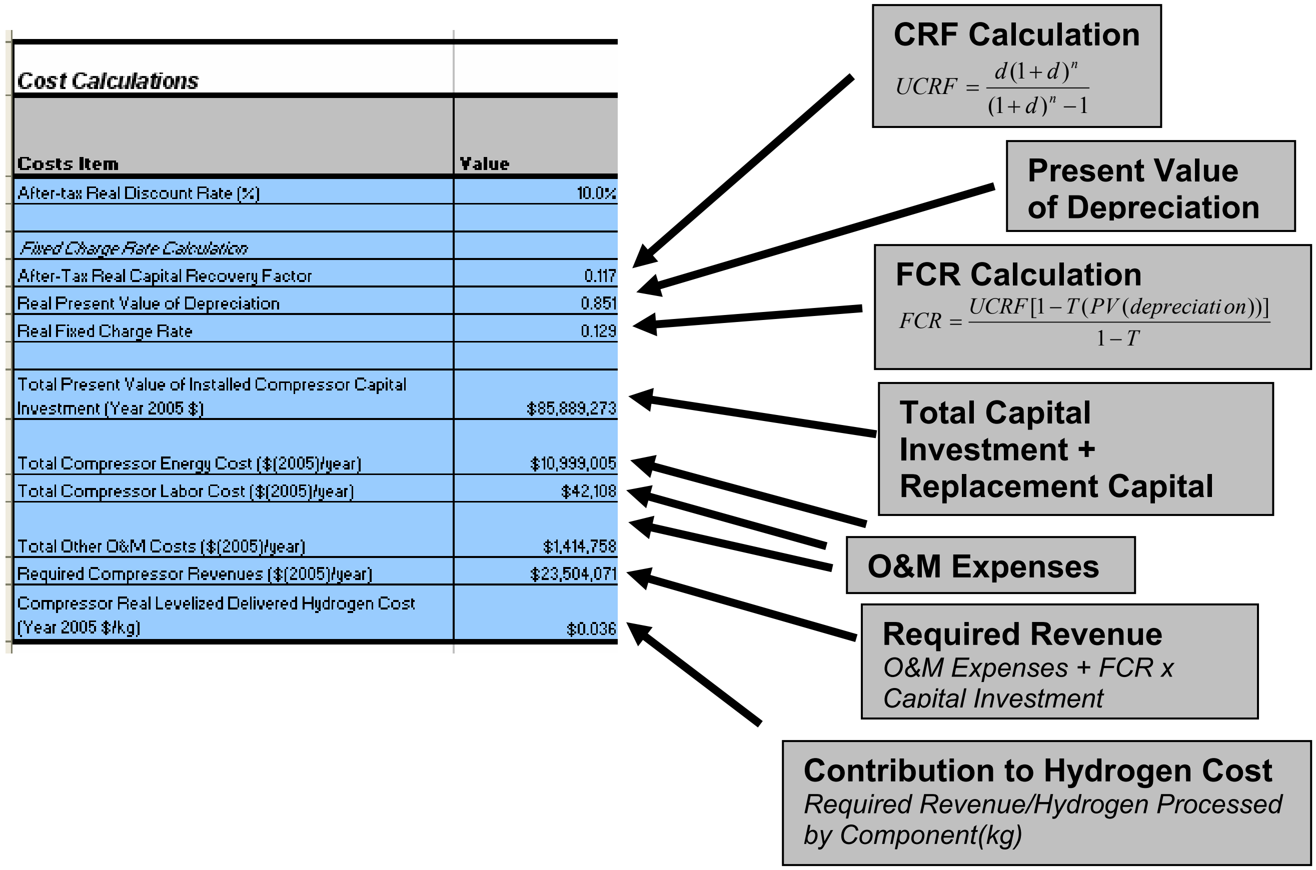
	Base Case	H2A Base Case	Comments	Data source
Assumed start-up year	2005	2005	This start-up year represents a near term case	H2A
Reference year dollars	2005	2005	As a base case, all H2A analyses are based on year 2005 dollars	H2A
Real After-tax Discount Rate (%)	10.0%	10%	This discount rate is used throughout the H2A analyses	H2A
MACRS Depreciation Schedule Length (years)	5	5	Taken from IRS Publication 946, Table B-2 "Certain Property for Which Recovery Periods Assigned - Qualified Technical Equipment"	IRS
Compressor Lifetime (years)	5	5		H2A
Analysis Period (years)	20	20	This is the base analysis period of H2A cases.	H2A
Inflation Rate (%)	1.9%	1.9%	Reference inflation for H2A cases is 1.9% per year	H2A
State Taxes (%)	6.0%	6%		H2A
Federal Taxes (%)	35.0%	35%	Corporate Tax Bracket - H2A standard	H2A
Total Tax Rate (%)	38.9%			

Figure 9. Economic Assumptions table from the Hydrogen Compressor tab.

The Economic Assumptions table, as mentioned previously, is where all the economic and financial parameters are entered. Each tab will required the same inputs. However, for some tabs, where more than one component is included, the user will be required to enter more than one lifetime and depreciation schedule. The inputs for the Economic Assumptions table are described below:

- <u>Assumed start-up year</u>: Enter the year that the component will first be used. For base case analyses, the H2A delivery team assumes 2005.
- <u>Reference year dollars</u>: This cell is locked at 2005, which corresponds with the feedstock costs used in the model. A user will notice that anytime a $ input is required or reported, the label specifically mentions 2005 dollars.
- <u>Real After-tax Discount Rate</u>: The discount rate is used in calculating the fixed charge rate. It is the return that the investor(s) want to make on their initial capital outlay.
- <u>MACRS Depreciation Schedule</u>: MACRS is the depreciation schedule specified by the Internal Revenue Service. Therefore, it is recommended that the user reference IRS Publication 946 ("How to Depreciate Property", available at http://www.irs.gov/publications/p946) for the proper depreciation schedule for a particular component. The H2A Delivery Team has included suggested values, which correspond to values in Publication 946.
- <u>Component Lifetime</u>: Enter the length of time that the particular component will last before needing replacement.
- <u>Analysis Period</u>: Enter the length of time over which the user wants the analysis to be carried over.
- <u>Inflation Rate</u>: Enter a yearly inflation rate for use in the analysis. In the Delivery Components model, this number is only used for calculating the cost of replacement capital.
- <u>State Taxes</u>: Enter the state or local tax rates that the component will be subjected to when in operation.
- <u>Federal Taxes</u>: Enter the federal tax rate that will apply to the particular component.

In the table from the compressor tab, the discount rate is assumed to be 10%, the MACRS depreciation schedule is 5 yrs, the compressor lifetime is 5 years and the analysis period is 20 years. These numbers, along with total tax rate of 38.9% are used to calculate the FCR.



Cost Calculations	
Costs Item	Value
After-tax Real Discount Rate (%)	10.0%
Fixed Charge Rate Calculation	
After-Tax Real Capital Recovery Factor	0.117
Real Present Value of Depreciation	0.851
Real Fixed Charge Rate	0.129
Total Present Value of Installed Compressor Capital Investment (Year 2005 $)	$85,889,273
Total Compressor Energy Cost ($(2005)/year)	$10,999,005
Total Compressor Labor Cost ($(2005)/year)	$42,108
Total Other O&M Costs ($(2005)/year)	$1,414,758
Required Compressor Revenues ($(2005)/year)	$23,504,071
Compressor Real Levelized Delivered Hydrogen Cost (Year 2005 $/kg)	$0.036

Figure 10. Cost Calculations table from the Hydrogen Compressor tab with descriptions.

Figure 10 shows how the final contribution to the hydrogen cost for a particular component is calculated. The after-tax real discount rate listed in the Economic Assumptions tab is used to calculate the after-tax real CRF. The same discount rate, along with the MACRS depreciation schedule, is used in calculating the real present value of depreciation. These two numbers are then used to determine the FCR.

Based on the input in the components tab, the present value of the capital investment and future allocations for replacement capital is $85,889,273. The sum of the O&M expenses, separated into energy, labor and other, comes to $12,455,871. When these O&M expenses are added to the product of the FCR and the present value of the capital investment, the total required annual revenues for this compressor to satisfy the 10% after-tax discount rate assumption total to $23,504,071. This number is then divided by the net hydrogen processed by the compressor (653,715,000 kg/year for this example) gives a hydrogen cost contribution of $0.036/kg of hydrogen.

The cost calculations for the other components will look very similar to the one shown in Figure 10. Some of the tabs, which contain more complex scenarios, will have particular components separated out in the Cost Calculations table (i.e. storage and compression are separated in the Compressed Gas H2 Terminal tab), but the labels and the calculations are analogous to those shown in Figure 10.

4.0 General Comments

There are some items that are similar in each component tab. Rather than discuss these items when describing each tab, they will be discussed in this section. The items to be discussed include the following.

1) The "Trendlines can't be calculated using 0 value" message that appears periodically
2) Calculation of the Compressibility Factor (Z-factor) for components processing gaseous hydrogen
3) Gas constant
4) System energy use
5) Mass and system efficiencies
6) Compressor power requirements

4.1 "Some Trendlines Cannot be Calculated From Data Containing Negative or Zero Values" Message

Periodically, the message shown in Figure 11 will appear when starting up or using the H2A Delivery Components model. We have not been able to determine why this message appears. We believe that some of the graphs that are used in the model may be based on data that includes a 0 value. Regardless, the message does not in any way affect the final result. When this message appears, simply hit the "OK" button, and continue with your work.

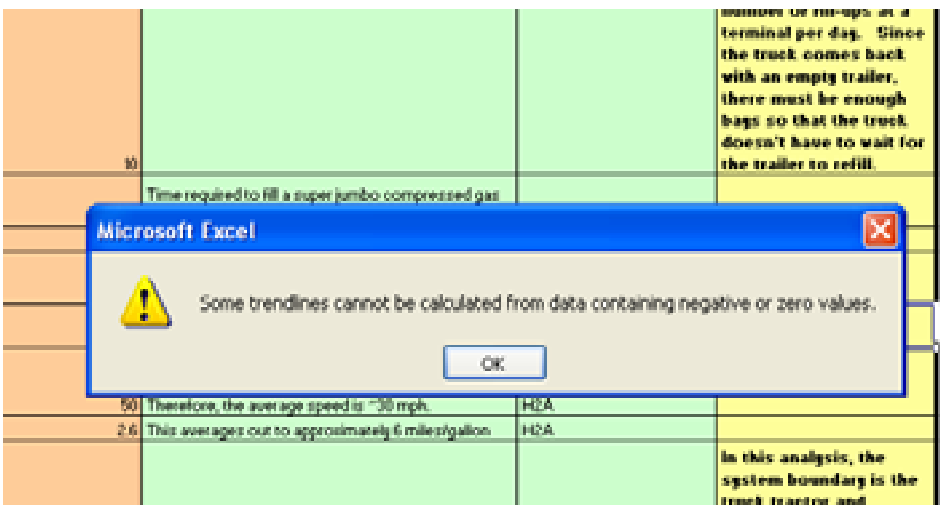


Figure 11. Error Message that may periodically appear when using the H2A Delivery Components Model

4.2 Compressibility Factor (Z-factor) Calculation

In each component tab that processes gaseous hydrogen, a background macro calculates the compressibility factor based on user inputs. For this project, a simple hydrogen equation of state (EOS) suitable for use in an Excel spreadsheet was developed. We wanted to develop an equation or set of equations that would give compressibility factors of engineering accuracy in the range of conditions for hydrogen storage and delivery: near 20 to 30°C and 1 to 700 atm. A Redlich-Kwong (RK) cubic EOS with its parameters tuned to data from the NIST Web Book2 was found to give compressibility factors within ±0.3% accuracy (Daubert, T.E., 1985; NIST Web Book). The RK EOS has the pressure explicit form of:

$$P = \frac{RT}{\tilde{V} - b} - \frac{a}{T^{1/2}\tilde{V}(\tilde{V} + b)}$$

and the compressibility factor form of:

$$Z^3 - Z^2 + [A - B(B+1)]Z - AB = 0$$

where the symbols have the following meanings and typical units:
P pressure (atm)
T temperature (K)
V molar volume (L/mol)
R gas constant (0.08205791 L·atm/K·mol)
Z compressibility factor (defined as PV/RT)
a RK attraction parameter
b RK co-volume parameter
A dimensionless RK attraction parameter
B dimensionless RK co-volume parameter

and the dimensionless RK parameters are defined as:

$$A = \frac{Pa}{R^2 T^{2.5}} \quad \text{and} \quad B = \frac{Pb}{RT}.$$

The RK parameters are normally estimated from the critical pressure and temperature (P_c and T_c, respectively) of a fluid:

$$a = 0.42748 \frac{R^2 T_c^{2.5}}{P_c} \quad \text{and} \quad b = 0.08664 \frac{RT_c}{P_c}.$$

For hydrogen, with P_c = 12.978 atm and T_c = − 240.0 °C = 33.15 K (NIST Web Book), the RK parameters should be a = 1.4033 and b = 0.018160 . However, a comparison to data from the NIST Web Book found that a better match to the downloaded data in the pressure and temperature range of interest was given by parameters a = 0.42750 and b = 0.016574.

The compressibility factor form of the RK EOS is cubic in Z . It is solved analytically for all three real roots and the largest value returned as the appropriate value (Press et al, 1992).

4.3 Gas Constant

In each component tab where gaseous hydrogen is processed, a gas constant is given. Because the model was developed using metric units, the value of the gas constant is:

8.3144 kJ/K.kg-mol

4.4 System Energy Use

The Results Table at the top of each delivery component tab contains one row for System Energy use. The units for this value are MJ/kg of hydrogen out of the system. In the following tabs, the System Energy use is 0 because either none or no insignificant amount of external energy is required for the operation of the component:

- Forecourt Dispenser (electricity required is insignificant)
- H2 Pipeline (compressor is not included in this tab)
- Bulk Liquid Hydrogen Storage (liquefier and pumps are not included in this tab)
- Compressed Gas Storage Tubes (compressor not included in this tab)
- Forecourt Storage (compressor not included in this tab)
- Liquid H2 Terminal (liquefier is not included, and pumps take an insignificant amount of energy)

In all the other tabs, the system energy use is calculated by dividing the utility usage per year (calculated in the O&M costs tab) by the amount of hydrogen out of the component. The hydrogen out of the component is equivalent to the Net Hydrogen Delivered (typically calculated in the Calculations table).

4.5 Mass and System Efficiencies

The Results Table at the top of each delivery component tab also contains two other rows: one for mass efficiency and one for system efficiency. The mass efficiency is calculated according to the following formula:

$$\eta_{mass} = \frac{H_{2,out}}{H_{2,in}}$$

Where:

$H_{2,out}$ = net hydrogen delivered by the component (calculated in the Calculations table)
$H_{2,in}$ = the average daily hydrogen flowrate out, multiplied by 365 and then divided by (1-losses).

The system efficiency is calculated on an LHV basis according to the following formula:

$$\eta_{syst} = \frac{H_{2,out}(LHV)}{H_{2,in}(LHV) + ExternalEnergy(LHV)}$$

The LHV of the hydrogen out of the system is determined by $H_{2,out}$ from the mass efficiency calculation multiplied by the lower heating value of hydrogen. The LHV of the hydrogen into the system is calculated by multiplying the $H_{2,in}$ from the mass efficiency calculation by the lower heating value of hydrogen. The external energy LHV is calculated by multiplying $H_{2,in}$ by the System Energy use (described in the previous section). The system efficiency defined in the H2A Delivery Components model is consistent with the definition used by the Department of Energy's Hydrogen Program.

4.6 Compressor Power Requirements

The proper selection for any type of compressor requires information about operating conditions (i.e. type of gas, inlet pressure, outlet pressure, temperature, molecular weight) as well as corrosion parameters (proper selection of materials of construction). The H2A Delivery Components model is not a compressor design tool per se, and thus a simplified methodology for calculating the theoretical power requirement is used. The equation listed below calculates the theoretical power requirement for a single or multi-stage compressor assuming that the compression work is equally divided between the stages and that an intercooler between each stage brings the gas temperature back to the original inlet temperature (Peters and Timmerhaus, 2003).

$$P_{th} = \dot{m}\, ZRT_1 N_{st}\left(\frac{k}{k-1}\right)\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{kN_{st}}} - 1\right]$$

In the above equation,

P_{th} = theoretical power requirement
m = mass flow rate
Z = compressibility factor
R = gas constant
T_1 = inlet gas temperature
N_{st} = number of compression stages
k = heat capacity ratio (1.4 for hydrogen)
p_2 = outlet pressure
p_1 = inlet pressure.

The actual power used in compression is determined by dividing the theoretical power requirement by the isentropic efficiency, which is a user-input value.

4.7 Fuel/Utility Costs

Some of the components modeled in this model require some type of utility for operation. For example, a truck to deliver compressed gas hydrogen or liquid hydrogen requires diesel fuel to move from the terminal to the forecourt station.

In the overall H2A effort, one of the goals was to provide analyses based on consistent assumptions. To this end, a table of typical feedstock and utility cost projections, based on data from the Energy Information Agency, was developed. This table, described in more detail in a later section of this manual, is also included in the Components Model. However, it is not used as it is in the H2A Central and Forecourt Production cases. For users' familiar with the H2A Production cases, you will recall that for each year in the analysis period, a separate feedstock cost is used for each year in the analysis period. For example, a central natural gas reformer with a startup year of 2005 and an analysis period of 10 years would use the 2005 natural gas cost production for the first year of the analysis period, the 2006 natural gas cost for the second year of the analysis period, the 2007 natural gas cost for the third year of the analysis period, and so forth. In the H2A Delivery Components model, only the feedstock or utility cost projection for the reference year is used. Because a discounted cash flow method is not used, and a cash flow table for each year of the analysis period is not developed, only a single feedstock or utility cost projection is pertinent in the Components Model.

The following components tabs have utility and/or feedstock requirements.

1. Forecourt Station – Gaseous Hydrogen
2. Forecourt Compressor
3. GH2 Tube-Truck Delivery_2700psi
4. GH2 Tube-Truck Delivery_7000psi
5. Compressed Gas H2 Terminal
6. Truck – LH2 Delivery
7. H2 Liquefier
8. H2 Compressor
9. Gaseous H2 Geologic Storage

On each tab where fuel/utility costs are required, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab using a yes/no toggle. If ***yes*** is selected, then the model uses a look-up function to search the feedstock table for the fuel/utility cost in the start-up year. The value pulled from the table appears in a blue cell directly below the yes/no toggle switch. To calculate the annual fuel cost, the Fuel Cost from the table is multiplied by the fuel/utility consumption.

If ***no*** is selected, the "Fuel Cost" disappears in the cell below the yes/no toggle switch, and a new cell requesting the user to input a fuel/utilty cost appears. The units for a specific Component utility/fuel requires is also specified in this cell. The user-entered value is then multiplied by the fuel/utility consumption to determine the annual fuel cost.

4.8 Component Flowrates

To properly design any processing component, it is imperative that an engineer knows two variables:

1. Average Flowrate: During an operating year, a component in the hydrogen infrastructure will see varying flowrates depending on, for example, the season, the day of the week,

and the hour of the day. This phenomenon is similar to what current gasoline delivery infrastructure experiences. For example, the demand will be higher in summer, on weekends and at different times of the day. These high demand periods are often referred to as peaks. If the peaks are normalized with all other demands during a year, the result is a constant, or “Average” demand.

2. Peak Flowrate: The peaks that occur during the year determine what the peak flowrate will be.

Based on these two numbers, the design capacity of a specific component, as well as its annual energy consumption can be calculated. The design capacity is based on the peak flowrate because the specific component will need to be sized to handle this amount of flow. The annual energy calculation can be determined based on the average flowrate.

In the H2A Components model, both the Average and Peak Demand flowrates are modeled. In all cases, they are based on the flowrates out of the component. Therefore, because losses might occur during the feed processing, the feed flowrate may actually be higher.

A term which is used to describe the ratio between the average flowrate and the peak flowrate is the capacity factor. This value describes, on average, the percent of the design capacity for the component that is being utilized. For example, if the average flowrate to a forecourt compressor is 70 kg/hr, but the peak or design capacity flowrate is 100 kg/day, the unit is operating at a 70% capacity factor.

4.9 Labor Costs

The amount of labor and thus the labor costs for some of the components in this model can be a function of the component capacity. However, because most of the tabs have labor costs as a manual entry, these costs will not be scaled with increases or decreases in capacity. The user will need to consider potential increases or decreases in labor costs as capacity changes, and make proper adjustments as necessary.

The following tabs have automatic labor cost calculations, which means these costs will be scaled based on capacity.

- GH2 Truck-Tube Delivery_2700psi
- GH2 Truck-Tube Delivery_7000psi
- Truck LH2 Delivery.

4.10 Other Costs as a Function of Capacity

Some of the other costs that are entered in the model will vary with component capacity. The following tabs contain H2A Delivery Team cost curves that will vary with component capacity so long as the user has opted to use the curves.

- Forecourt Station - Gaseous H2
- Forecourt Station – Liquid

- Forecourt Compressor
- Forecourt Dispenser
- Forecourt Storage
- Compressed Gas H2 Terminal
- Compressed Gas H2 Storage Tubes
- Liquid H2 Terminal
- H2 Liquefier
- Bulk Liquid Hydrogen Storage
- H2 Compressor
- H2 Pipeline
- Gaseous H2 Geologic Storage.

In these tabs, the majority of the O&M costs will also vary directly with component capacity, as most of the required entries tie directly to the total capital investment.

5.0 Single Component Tabs in the H2A Components Model

In the next two sections, each tab in the component model is described in detail. The first tabs discussed will be the Title Worksheet, the Feedstock and Utility Prices Worksheet tab, the Physical Properties tab and the MACRS Depreciation tab. Next, each single component tab will be covered in the order of presentation in the model. In the next section (6.0), the mini-scenario, or combined component, tabs are presented in the order that they appear in the model. The cost and data tabs at the end of the model (Liquefier Cost_Efficiency, Liquid Storage Costs, Pipeline – OGJ, Large Comp. Costs) are discussed in the tab description for the component to which the refer.

5.1 Title Worksheet Tab

The title tab links the data in the model with the individual who programmed the data in. The primary purpose for its inclusion is so the model can be shared without losing the name of the person or persons who originally developed it. Explanations about what needs to be included in the each cell are shown in the Table 1.

	Instructions:
Title:	*Enter a title for the case being analyzed and reported on.*
Authors:	*Enter the name of the original author of the analysis being entered into the H2A tool.*
Contact:	*Enter your name.*
Contact phone:	*Enter your phone number.*
Contact e-mail:	*Enter your e-mail address.*
Organization:	*Enter your company/organization name.*
Date Spreadsheet was Last Modified:	*Enter the most recent date that the spreadsheet was last modified.*
Web site:	*Enter the web site where additional information can be found for the case being entered into the H2A tool, including reports on the original analysis, if applicable.*
Purpose	
This space should be used to describe what type of analysis is being completed using the H2A Delivery Components Model.	
Reporting Spreadsheet Change History:	
Date spreadsheet created / modified	Name
	These spaces should be used to keep a log of changes made to the case studied.

Table 1. The title page table with a cell by cell description of what the user needs to include.

5.2 Feedstock and Utility Prices Worksheet Tab

The feedstock and utility prices tab, which is common to all H2A, can be used to select feedstock and utility costs. The various component tabs pull information from this tab. The H2A Components model also allows the user to enter their estimations of feedstock and utility prices.

Projections for the following feedstocks and utilities were derived from the *Annual Energy Outlook 2005* (AEO) developed by the U.S. Department of Energy's Energy Information Administration (EIA). The data for both the High A Oil and Reference Oil EIA scenarios are included in this model. A toggle switch on the Feedstock and Utility prices tab allows the used to select whether to use the High A or Reference cases (cell C17).

- Commercial Natural Gas
- Industrial Natural Gas
- Electric Utility Natural Gas
- Commercial Electricity
- Industrial Electricity
- Electric Utility Steam Coal
- Diesel Fuel
- Gasoline
- Biomass

EIA makes projections for every year between 2000 and 2025. These prices are provided in constant 2003 dollars per million (MM) British Thermal Unit (Btu) and in constant 2003 $ per physical unit (e.g. $/ton of coal, $/cubic foot of gas, etc.). Note that EIA does not provide the biomass prices in their published *AEO* reports, but the projected biomass prices were obtained by special request.

AEO prices in dollars per physical unit are based on standard thermal conversion factors available in Appendix H of the *AEO* publication. These 2003$ *AEO* values were converted to reference year (2005) $ using GDP Implicit Price Deflator available from EIA in *Annual Energy Review* 2003, Table A-20. They were converted from Btus to Gigajoules (GJ) using 1.055 GJ/MMBtu.

For the period between 2025 and 2035, the values were simply extrapolated using the 2015-2025 growth, i.e., the ratio of the EIA 2025 value to the EIA 2015 value was multiplied by the EIA 2025 value to obtain the 2035 value. Values between 2025 and 2035 were interpolated.

For the period between 2035 and 2070, for all feedstocks and utilities listed above except for biomass, the prices were extrapolated using price projections from the MiniCAM model developed by Pacific Northwest National Laboratory (PNNL).[1] The specific projections used are columns E, F, G, H and I of rows 116 through 125. The projected prices from MiniCAM were converted into ratios (columns B, C and D of rows 104-111) that were applied to the values derived from EIA. Wellhead gas price ratios from Mini-CAM were applied to all sectoral gas prices except utilities, which are separately projected. Average electricity price growth rates from Mini-CAM were applied to all sectoral electricity prices, and crude oil price growth rates were applied to diesel fuel and gasoline.

The biomass prices for the projected prices were based on a review of literature. Biomass prices shown for years 2001 through 2009 are the same as the EIA value for 2010. For the post-2025 biomass prices, the value for 2035 was chosen based on a review of the literature that indicated a price of $2.50/MMBtu delivered dry English ton (in 2000$) was a reasonable mid-range projection. Values for the 2026 through 2034 were interpolated from the 2025 and 2035 values. The value of $5.00/MMBtu delivered dry English ton in 2065 was based on judgment. An EIA paper by Zia Haq entitled, "Biomass for Electricity Generation" (available from EIA's website) indicates that about 7 quads of biomass per year would be available if the price rose to $5/MMBtu.

This tab contains H2A data for many of the feedstocks and fuels that can be used to produce hydrogen. For consistency, analyses being done using the H2A modeling tool should use the values shown in this worksheet tab.

5.3 Physical Property Data Worksheet Tab

Just like the feedstock and utility tab, the physical properties tab is common to all H2A models. Several energy sources are being considered as feedstocks for production of hydrogen. For GREET simulations of carbon emissions and evaluations of hydrogen production processes, physical properties of these feedstocks are needed. This tab documents physical properties of several feedstocks based on Argonne's research and inputs from Directed Technologies, National Renewable Energy Laboratory, and Parsons. Although feedstock properties can be different for the same feedstock from different production or consumption sites, it is intended here that

[1] MiniCAM models the global energy and industrial system, including land use, in an economically consistent global framework. MiniCAM is referred to as a *partial equilibrium model* in that it explicitly models specific markets and solves for equilibrium prices only in its areas of focus: energy, agriculture and other land uses, and emissions. The supply and demand behaviors for all of these markets are modeled as a function market prices, technology characteristics, and demand sector preferences. Market prices, including feedbacks between energy markets, are adjusted until supply and demand for each market good are equal. At this equilibrium set of prices, production levels, demand, and market penetration are mutually consistent. For example, gas production will increase with a rise in gas price, which drives a decrease in gas demand. In equilibrium, these market clearing prices (e.g., the prices of gas, coal, electricity, etc.) are by definition internally consistent with all other prices. And in parallel, all supply and demand behavior is consistent with assumptions about the key model parameters and drivers, including the following: (1) technology characteristics (from production to end-use), (2) fossil fuel resource bases (cost-graded resources of coal, oil, and natural gas); (3) renewable and land resources (hydroelectric potential, cropland, etc.); (4) population and economic growth (drivers of demand growth); (5) policies (about energy, emissions, etc.). The MiniCAM is based on three end-use sectors (buildings, industry, transportation) and a range of energy supply sectors, including fossil-fuels, biomass (traditional biomass such as use of wood for heat, and modern biomass that can be used as a fuel for electricity production or as a feedstock for bio-fuels or hydrogen production), electricity, hydrogen, and synthetic fuels. For electricity generation, the model's technological detail covers generation from coal, oil, natural gas, biomass, hydroelectric power, fuel cells, nuclear, wind, solar photovoltaics, electricity storage (e.g., coupled with production of electricity using solar and wind generation), and exotic technologies such as space solar and fusion.

national average properties be summarized for H2A. In this summary, physical properties for the following feedstocks are presented.

1) Biomass ─ Switchgrass
2) Biomass ─ poplar
3) Coal
4) Natural gas
5) Ethanol
6) Methanol
7) Gasoline (without oxygenate)
8) Conventional diesel
9) Low-sulfur diesel
10) Gaseous hydrogen
11) Liquid hydrogen

Among the 11 feedstocks and fuels, the first six are feedstocks for hydrogen production either at central plants (in the cases of switchgrass, poplar, coal, and natural gas) or at forecourt (in the cases of natural gas, ethanol, and methanol). Gasoline and diesel are presented here for calculating energy and emissions of well-to-pump activities in spreadsheet models developed through the H2A effort. Gaseous and liquid hydrogen are presented here for conversion between feedstocks and hydrogen.

A literature search, together with summary of what is already in the GREET model, was conducted to obtain the following physical properties for each of the above feedstocks:

1) Lower heating value
2) Higher heating value
3) Density
4) Carbon content by weight
5) Hydrogen content by weight.

For switchgrass, woody biomass, and coal we also investigated the typical moisture content. The literature search revealed that these physical properties have range of values. Mean values, as well as low and high values, were computed from these ranges and are presented here. Densities are provided for ethanol, methanol, and natural gas to facilitate conversion from their volumetric units to weight.

The literature survey provided only the higher heating value for biomass and coal. In H2A and GREET simulations, energy balance calculations will be conducted with lower heating values, as in many other studies. The lower heating values for switchgrass, wood, and coal were computed by using the following general relationship between higher and lower heating values (Himmelblau 1996; SAE 1998).

$$LHV = HHV - 91.23 \times H_2$$

Where,

LHV = Lower heating value in Btu/lb

HHV = Higher heating value in Btu/lb

H_2 = Hydrogen fraction by weight in percentage

5.3.1 References for Physical Properties Data Worksheet Tab

Numerous references are used for data shown in the H2A model Physical Properties Data Worksheet tab, and these are listed below.

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5.4 MACRS Depreciation Table

In the H2A Delivery Components model, Modified Accelerated Cost Recovery System (MACRS) depreciation is used. The MACRS method is prescribed by the IRS for use in tax accounting. The H2A spreadsheet uses the 200%/half-year convention MACRS method.

The H2A Delivery team has assigned base depreciation periods for each component tab. In general, the depreciable lifetimes are based on IRS Publication 946 (available at http://www.irs.gov/pub/irs-pdf/p946.pdf). In this document, the IRS lists the assigned lifetimes for specific assets.

The depreciation period for each component may be different. Therefore, each component tab has a separate depreciation table on this tab. A sample table is shown below in Table 2.

Truck-Tube Trailer

MACRS Depreciation Period						
Depreciation Period	3	5	7	10	15	20
1	33.33%	20.00%	14.29%	10.00%	5.00%	3.750%
2	44.45%	32.00%	24.49%	18.00%	9.50%	7.219%
3	14.81%	19.20%	17.49%	14.40%	8.55%	6.677%
4	7.41%	11.52%	12.49%	11.52%	7.70%	6.177%
5		11.52%	8.93%	9.22%	6.93%	5.713%
6		5.76%	8.92%	7.37%	6.23%	5.285%
7			8.93%	6.55%	5.90%	4.888%
8			4.46%	6.55%	5.90%	4.522%
9				6.56%	5.91%	4.462%
10				6.55%	5.90%	4.461%
11				3.28%	5.91%	4.462%
12					5.90%	4.461%
13					5.91%	4.462%
14					5.90%	4.461%
15					5.91%	4.462%
16					2.95%	4.461%
17						4.462%
18						4.461%
19						4.462%
20						4.461%
21						2.231%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
NPV (Real)	0.832	0.773	0.721	0.654	0.517	0.442

Table 2. Sample depreciation table from the deprecation table tab.

The depreciation periods are shown across the second row of the table. Below each period, the specific portions of the capital that are depreciable in the specific year after purchase are listed. For example, in its fifth year of operation, a capital asset with a 20-year depreciable period will have 5.713% of its original value depreciated.

As described in the financial analysis section of this manual, the important depreciation calculation that is used in the fixed-charge rate calculation is the net present value of the depreciable amounts. This calculation is shown at the bottom of each row in the table. The NPV function in Excel is used to determine the value.

5.5 Forecourt Compressor

This tab is used to calculate the contribution to the delivered hydrogen cost for a forecourt compressor. This compressor is used at the forecourt to compress the hydrogen to the pressure required in the on-board storage vessel. Additionally, it can be used to pressurize gas for storage in compressed storage tubes. A forecourt compressor is significantly different from a central, or larger-scale, compressor. The higher outlet pressures required, as well as the significantly smaller flowrates, are two of the major differences. Additionally, different types of compressors, such as diaphragm units, will not work in the central compression cases, but may be viable for forecourt applications.

Figure 12. An example of a diaphragm compressor that can be used to compress hydrogen at a forecourt station (photo was downloaded from PPI Industries website at www.pressureproducts.com)

5.5.1 Design Concept

The forecourt compressor tab is designed to cost a compressor that can raise the pressure of a defined hydrogen flowrate from one pressure to the pressure required for on-board vehicle storage. A separate tab is used to calculate the cost of a larger-scale, central compressor. The model includes an idealized compressor power calculation (defined in the introduction), or the user can opt to cost the compressor based an input of kW/kg of hydrogen/hour.

In many hydrogen compression applications, the compressor units are spared to ensure a high level of operational availability. Sparing is extremely important when considering reciprocating compressors. To this end, the tab allows the user to enter the number of purchased compressors along with the number of compressors operating at any one time.

5.5.2 Key Assumptions

- The user needs to know either the number of stages in the compressor or the compression ratio per stage. In selecting these values, the user must ensure that typical material temperature constraints are not exceeded, as the model does not check interstage or exit temperatures.
- The theoretical power requirement calculation assumes that the compression work is equally divided between the stages and that an intercooler between each stage brings the gas temperature back to the original inlet temperature.
- It is assumed that there are not pressure drops in the after-cooler or interstage coolers.
- An electrical-powered compressor is assumed. The tab does not allow for the calculation of costs associated with compressors fed with other fuels such as natural gas or hydrogen.

5.5.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Forecourt Compressor Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

5.5.4 Design Inputs

The design inputs table is used for entering values that determine the size of the compressor required. This table contains a number of yes/no toggle switches, which enhance the flexibility of the model. The items included in this table are described below.

- Average Hydrogen Out: Enter the average hydrogen flowrate out of the compressor in kg/day. Please note that this entry is the amount of hydrogen that you actually want to have delivered from the compressor. The value entered in this cell will be increased in the calculation section if any hydrogen is assumed to be lost during the compression process (hydrogen losses are entered in a later cell).

- Peak Hydrogen Flowrate Out: Enter the peak hydrogen flowrate out of the compressor in kg/day.

- Inlet Pressure: The user should enter the suction pressure to the compressor in this cell. It is important to note that no vacuum pressures can be entered.

- Outlet Pressure: The user should enter the compressor outlet pressure in this cell. It is important to note that no vacuum pressures can be entered.

- Inlet Hydrogen Temperature: Enter the temperature of the hydrogen gas entering the suction end of the compressor.

- C_p/C_v Ratio: Enter the ratio of the constant pressure specific heat for hydrogen and the constant volume specific for hydrogen. H2A uses a value of 1.4 for this ratio.

- Enter the Number of Installed Compressors: As mentioned earlier in this section, to ensure high compressor availability, compressors may need to be spared. Enter the number of compressors that will be purchased in this cell.

- Enter the Number of Compressors in Operation at Any Time: Enter the number of compressors that will be processing hydrogen. For example, a user may enter 3 as the number of compressors required, but only have 2 operating at any one time. In that instance, one compressor is a spare.

The next cell, labeled "Design Compressor based on a Compression Ratio per Stage?", contains a yes/no toggle switch. A compression ratio per stage is defined as the outlet pressure from the stage divided by the inlet pressure to that stage. If ***yes*** is selected, the user must enter a value in the following cell:

- Enter Compression Ratio per Stage: The design compressor ratio per stage needs to be entered in this cell. The model will use this value to calculate the number of stages required for the compressor.

If ***no*** is selected, the user must enter a value in the following cell:

- Enter the Number of Stages: The number of stages in the compressor should be entered. The model will calculate the pressure ratio.

The next important consideration for the user is the isentropic compressor efficiency. The cell, labeled "Isentropic Compressor Efficiency Available?", includes a yes/no toggle switch. The isentropic efficiency is determined by assuming that the compressor process occurs without an increase in entropy. If ***yes*** is selected with the toggle switch, the user must enter a value in the following cell:

- Isentropic Compressor Efficiency: Please enter the isentropic compressor efficiency in this cell. This value is used to calculate the actual power consumed by the compressor.

If ***no*** is selected, the user must enter values in the following cells:

- Type of Efficiency Available: Since the isentropic efficiency of the compressor is not available, the user needs to specify the type of compressor efficiency that is available.

- Compressor Efficiency: The user should enter the compressor efficiency as described in the previous cell. Since the isentropic efficiency is not available, the model will use this efficiency to calculate the actual power consumed by the compressor.

As mentioned previously, the user can opt to use the idealized compressor power equation described previously, or simply enter the kW/kg of hydrogen/hour required for compressor. Therefore, the next cell, labeled "Use Isentropic Efficiency to Calculate the Power Requirement", is a yes/no toggle switch. If ***no*** is selected, then a value needs to be entered into the following cell:

- Compressor Power Requirement: Please enter the power draw for the compressor, in kW/kg of hydrogen/hour, for the compressor under investigation.

If ***yes*** is selected, no further input is required.

- Hydrogen Lost During Compressor: Please enter the amount of hydrogen that is lost during the compression process as a percentage of the feed flowrate.

- Type of Compressor: Please use the pull-down menu to select the type of compressor described by the input data. This is an optional entry, but is useful for other users to understand what type of compressor was envisioned.

5.5.5 Calculations

Please see the Compressor Power Calculations section in the General Comments section of this manual for a detailed description of how the idealized power equation is defined.

- Gas Contant: The standard value of 8.3144 kJ/K.kg_mol is used in the H2A Delivery case.

- Mean Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual.

- Pressure Ratio: If a pressure ratio was entered in the Design Inputs table, then that value is simply fed to this cell. However, if the number of stages was entered, then the following formula is used to calculate the pressure ratio.

$$P_R = 10^{\frac{\log(P_{out}) - \log(P_{in})}{N_s}}$$

Where:

P_{out} = pressure out of compressor (from Design Inputs table)
P_{in} = inlet pressure to compressor (from Design Inputs table)
N_s = number of stages (from Design Inputs Table)

- Number of Stages: If the number of stages was entered in the Design Inputs table, then that value is simply fed to this cell. However, if the pressure ratio per stage was entered, then the following formula, rounded up to the nearest integer, is used to calculate the number of stages.

$$N_s = \frac{\log(P_{in}) - \log(P_{out})}{\log(P_R)}$$

Where the variables are defined as in the pressure ratio equation.

- Net Hydrogen Delivered Per Year: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 days/year.

- Design Flowrate to Each Compressor: This value is determined using the following equation:

$$F_{des} = \frac{F_{peak}}{N_c / 1 - loss}$$

Where:

F_{peak} = Peak hydrogen flowrate out (from Design Inputs table)
N_c = Number of compressors in operation at any time (from Design Inputs table)
loss = hydrogen losses (from Design Inputs table)

- Theoretical Power Requirement: The equation used in this cell was described in the General Comments section of this manual. The design flowrate to each compressor is used in this equation. N/A will show up in this cell if the user opted to enter a power requirement.

5.5.6 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.5.7 Capital Investment

This table is where the capital costs for the compressor are entered. There is far less data on the costs of forecourt compressors than on central compressors. Therefore, the H2A was not able to put together a cost curve for the forecourt compressor tab.

The specific entries for this table are described below.

- Number of Compressor Units: This value is linked to the number of compressors required, which was specified in the Design Inputs table.

- Compressor Cost per Unit: The user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Balance of Component: This item includes any other equipment that might be required for operation of a compressor that has not already been included in the previous items.

It is important to note that the capital cost entered for the compressor is on a per unit basis. The Balance of Component, on the other hand, should be entered on a net basis.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment. If ***yes*** was entered for using the H2A Compressor Capital Costs, no entry is required in the table, as the data from the Oil and Gas Journal used for the H2A capital cost curve included all the items. If the user opted not to use the H2A Compressor Capital Costs, then the following inputs are required.

- Land Required: Please enter the amount of land required for the forecourt compressor. This value should include any necessary safety offsets required around the compressor.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site (such as grating and pouring a cement base) should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of these compressors.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Installed Capital Cost: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.5.8 Operating and Maintenance Costs

In this table, the annual costs required for operating the compressor are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: The user should enter the total labor-hours per year required to operate the compressor.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.

- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

The annual energy requirement for the compressor is different from the value specified in the Capital Cost table. The capital cost of the compressor needs to be based on a unit that is capacle of processing the peak hydrogen flowrate. However, during a typical operating year, the feed flowrate will fluctuate. Therefore, the average hydrogen flowrate out is used as a basis to calculate the annual energy requirement (see the beginning of this manual for a discussion of peak and average flowrates).

If the user opted to use the idealized power equation, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 \frac{F_{avg}}{\eta_{isentrop}} ZRT_1 N_{st} \left(\frac{k}{k-1} \right) \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{kN_{st}}} - 1 \right]$$

Where:

$\eta_{isentrop}$ = isentropic compressor efficiency (from Design Inputs table)
F_{avg} = average hydrogen flowrate out, converted to mol/sec (from Design Inputs table)
R = gas constant (specified in the Calculation table)
T_1 = inlet gas temperature, converted to K (from Design Inputs table)
N_{st} = number of compression stages (calculated in the Calculations table)
k = ratio of specific heats (specified as Cp/Cv in the Design Inputs table)
p_2 = outlet pressure (specified in the Design Inputs table)
p_1 = inlet pressure (specified in the Design Inputs table).

If the user opted to input a compressor power requirement per kg/hr of hydrogen, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 P_{req} \frac{F_{avg}}{24}$$

P_{req} = Power requirement per kg/hr of hydrogen (from Design Inputs table)
F_{avg} = average hydrogen flowrate out (from Design Inputs table).

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total utility cost is determined by multiplying either the user-input fuel cost or the H2A value by the Annual Energy Requirement.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.

- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.5.9 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the compressors are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.6 Forecourt Dispenser

This tab is used to calculate the contribution to the delivered hydrogen cost for a hydrogen dispenser at the forecourt station. This tab can be used to determine the cost of multiple dispensers at a forecourt station.

Figure 13. A picture of an actual hydrogen dispenser (photo obtained from Air Products website, at www.airproducts.com).

5.6.1 Design Concept

This tab is used for designing and costing a forecourt hydrogen dispenser. A hydrogen dispenser, shown in Figure 13, looks very similar to natural gas dispensers.

5.6.2 Key Assumptions

- The tab is used to determine the cost of a dispenser for delivery of compressed hydrogen gas to a vehicle. A liquid dispenser is not modeled.
- No energy is required to operate the dispenser. In a real operation, electricity may be required to run internal components of the dispenser. But the amount of electricity is assumed to be small, and is not included in the calculated cost.
- The dispensing pressure is assumed by be 6,250 psia. The hydrogen gas will have been compressed to this pressure prior to entering the dispenser unit.

5.6.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Forecourt Dispenser Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

5.6.4 Design Inputs

The design inputs table is used for entering values to determine how much hydrogen will be delivered from the dispenser. This table contains yes/no toggle switches to enhance the flexibility of the model. The user has the option to either enter the number of dispensers, or to have the number of dispensers calculated based a 500 kg/day dispensing unit.

- Average Hydrogen Flowrate Out: Enter the average hydrogen flowrate out of the dispenser in kg/day.
- Peak Hydrogen Flowrate Out: Enter the peak hydrogen flowrate out of the dispenser in kg/day.
- Capacity Factor: Calculated by dividing the Average Hydrogen Flowrate Out by the Peak Hydrogen Flowrate Out.
- Calculate the Number of Dispensers Based on Flowrate?: The user needs to select either ***yes*** or ***no***.

  If ***yes*** is selected, then the number of dispensers will be calculated assuming that each unit has a capacity of 500 kg/day.

  If ***no*** is selected, then the user can enter the number of dispensers required.
- Enter Number of Dispensers Required: This cell only requires input if the user answered ***no*** to the question "Calculated the Number of Dispensers Based on Flowrate?". In that case, the user needs to enter the number of dispensers required.
- Dispensing Pressure: It is not necessary to enter a value in this cell. Please note, however, that the tab is designed assuming a dispensing pressure of 6,250 psia.
- Inlet Hydrogen Temperature: Although not required, the user can enter the temperature of the hydrogen fed to the dispenser.

5.6.5 Scenario Inputs

- Hydrogen Lost During Dispensing: Enter the amount of hydrogen, as a percentage of the Average Hydrogen Flowrate out, that is lost during dispensing.

5.6.6 Calculations

- Number of Dispensers: If ***yes*** was selected to the question "Calculate the Number of Dispensers Based on Flowrate?", then the value shown in this cell is calculated by dividing the Peak Hydrogen Flowrate Out by 500 kg/day, and then rounding up the result.

If ***no*** was selected, then the value shown in this cell is taken from the input to Enter the Number of Dispensers Required.

- Net Hydrogen Delivered: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 (days/yr).

5.6.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.6.8 Capital Investment

This table is where the capital costs for the compressed gas hydrogen forecourt dispenser are entered. Even though the number of dispensers is not shown in this table, the calculation in the "Calculated Installed Cost" column incorporates that value into the formula.

- Forecourt Dispenser (one with two hoses): The specific entries required in this row depend on whether the user has an uninstalled cost or an installed cost. For an installed cost, entry is only required in the column titled "User-Input Installed Cost". For an uninstalled cost, the user needs to enter values in the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Balance of Component: This item includes any other equipment that might be required for operation of a forecourt hydrogen dispenser that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment. The following items are either calculated, or require entry in this table.

- Land Required: The land required, in m^2, should be entered in this cell.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of the dispenser(s).

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Installed Capital Cost: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.6.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the hydrogen forecourt dispenser are entered. The table is divided into two sections: labor, and the remainder of costs. The forecourt dispensers do not require any significant energy for operation, and thus the user does not need to enter any fuel/utility information. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Maintenance Labor Requirement: The user should enter the total labor-hours per year required to maintain the forecourt dispensers.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.

- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.

- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.6.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor and other O&M costs for the compressed gas storage tubes are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.7 Forecourt Storage

This tab is used to calculate the contribution to the delivered hydrogen cost for compressed gas storage at the forecourt station. This tab can be used, for example, to calculate the cost of a cascade filling system, assuming that the user had previously sized the cascade system and knew the amount of storage that would be necessary.

5.7.1 Design Concept

This tab is used for designing and costing a forecourt compressed gas storage system. At this stage, compressed gas storage typically involves long, metallic pressure tubes. This tab has the flexibility to handle different types of compressed gas tubes, such carbon-wrapped units which could have a larger volume and also hold higher pressures that their metallic counterparts.

In a typical gas storage operation, the storage tubes are not allowed to completely empty. In other words, the storage tubes are considered to be empty when the pressure drops to a certain level. This tab is designed with the same philosophy. The user can enter a maximum storage pressure, and then a minimum storage pressure. The calculations will then determine the actual amount of hydrogen stored.

5.7.2 Key Assumptions

- The tab is used to size compressed gas forecourt storage only. Liquid storage is not modeled.
- No energy is required to operate the storage tubes. A compressor that may be required to get the hydrogen to the storage pressure can be sized, and its energy consumption determined, using the compressor tab.
- The storage system is assumed to be filled and emptied continuously during the year. Thus, the amount of hydrogen delivered from this component is calculated by multiplying the Average Demand from the storage system by 365 days/year.

5.7.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Forecourt Compressed Gas H2 Storage Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

5.7.4 Design Inputs

The design inputs table is used for entering values to determine how much hydrogen will be stored in the forecourt storage system. This table contains yes/no toggle switches to enhance the flexibility of the model. The user has the option to size the storage system based on an Average Demand on the storage system, the maximum and minimum pressures and the number of days of storage. Or, the user can simply enter the size of a storage system where the capacity is known.

If ***yes*** is selected by the user for the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Demand?", then the following inputs are required.

- Maximum Storage Pressure: The user should enter the maximum pressure of hydrogen that can be stored in the compressed gas storage tubes. Please note that this is not a design pressure. This is the maximum operating pressure of hydrogen that can be stored.

- Minimum Storage Pressure: The user should enter the minimum pressure of hydrogen that can be stored in the compressed gas storage tubes. As mentioned previously, the tanks are usually not completely emptied when they are considered depleted, and ready for a recharge of hydrogen.

- Operating Storage Temperature: Enter the temperature of the gaseous hydrogen held in this compressed gas storage system.

- Average Hydrogen Demand: Enter the average amount of hydrogen that the storage system needs to provide.

If ***no*** is selected for the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Demand?", then input is required only in the following cell.

- Enter the Capacity of the Compressed Gas Storage System: The user should enter capacity, in kg, of the compressed gas storage system that they would like to analyze. If this option is used, it is assumed that the user has considered minimum and maximum pressure in the vessel.

5.7.5 Scenario Inputs

- Number of Days of Storage: If the user answered ***yes*** to the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Capacity?", then the user needs to enter the number of days of storage desired. This input is multiplied by the average hydrogen demand (in conjunction with maximum and minimum pressures) to determined the size of the desired compressed gas storage system.

5.7.6 Calculations

- Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual. The compressibility factor is evaluated at the maximum pressure and the operating temperature.

- Design Tank Useable Capacity: The value calculated in this cell depends on how the user answered the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Demand?".

  If the user entered ***yes***, this value is calculated by multiplying the Number of Days of Storage by the Average Hydrogen Demand. It is important to note that this calculation does not take into account the maximum and minimum pressure requirements.

  If the user entered ***no***, the Capacity of the Compressed Gas Storage System, entered in the Design Inputs Table, is fed to this cell.

- Calculated Useable Tank Capacity: The value calculated in this cell depends on how the user answered the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Demand?".

  If the user entered ***yes***, this value is used to determine the actual size of the compressed gas storage system. There will be some gas left in the storage system when it is considered empty based on the minimum pressure entered in the Design Inputs table. Therefore, in order to meet the Average Demand and Number of Days of Storage requirements, the forecourt compressed gas storage system will need to be oversized. To calculate the percentage of the tank that is "useable", the following formula is used.

$$Frac_{use} = \frac{\frac{P_{\max}}{Z} - P_{\min}}{\frac{P_{\max}}{Z}}$$

  Where:

  P_{max} = maximum pressure in storage tubes (from Design Inputs table)
  P_{min} = minimum pressure in storage tubes (from Design Inputs table)
  Z = compressibility factor.

  If the user entered ***no***, then "N/A" appears because it is assumed that the user considered maximum and minimum pressure constraints when putting a value for the Capacity of the Compressed Gas Storage System.

- Design Tank Capacity: The value calculated in this cell depends on how the user answered the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Demand?".

  If the user entered ***yes***, this value is calculated by dividing the Design Tank Useable Capacity by the Calculated Useable Tank Capacity. The result of this calculation is the capacity that the storage tubes will have to contain in order to meet the maximum and minimum pressure requirements.

  If the user entered ***no***, the Capacity of the Compressed Gas Storage System, entered in the Design Inputs Table, is fed to this cell.

- Tank Volume: The result of the calculation used in this cell is for informational purposes only. The volume is calculated according to the following equation.

  $$V = \frac{C_{des} Z T_{oper} R}{P_{\max}}$$

  Where all the variables have been defined previously in this section except:

  C_{des} = Design Tank Capacity, converted to moles of hydrogen
  T_{oper} = operating temperature, converted to K (from Design Inputs table)
  R = gas constant, 8.2x10-5 psi/mol.K.

- Hydrogen Dispensed: This value is equivalent to the Average Hydrogen Demand.

- Net Hydrogen Delivered: This value is calculated by multiplying the Hydrogen Dispensed by 365 (days/yr).

5.7.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.7.8 Capital Investment

This table is where the capital costs for the compressed gas storage tubes are entered.

The H2A Delivery team has developed a cost function that can estimate the capital cost of compressed gas storage system. The cost is based on a value of $818/kg of hydrogen stored, which was obtained from the H2A Forecourt team. The cost figure represents a tank that can hold 6,250 psi of hydrogen.

The specific entries for this table are described below.

- Use the H2A Compressed Gas Storage Costs: The entry for this cell uses a yes/no toggle switch. If ***yes*** is selected, then:

  - The H2A compressed gas storage cost function, described above, is used for the compressor capital cost. Not other entry is required in the Capital Cost table.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Compressed Gas Storage Tank: The calculation in the "Compressed Gas Storage System Size (kg)" column reads the Design Tank Capacity of the compressed gas storage system that was calculated in the Calculations table. The specific entries required in this row depend on whether the user opted to use the H2A Compressed Gas Storage costs. If ***yes*** was selected, then the value in the "Installed Costs from H2A Data" is filled.

If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Balance of Component: This item includes any other equipment that might be required for operation of a compressed gas storage tube system that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment. The following items are either calculated, or require entry in this table.

- Use H2A Estimation for Compressed Gas Storage System size: The user is required to use select yes/no with the toggle switch. If ***yes*** is selected, a function to determine the amount of land required for the compressed gas storage system is used. This function is shown below.

  $$Land = 180(\frac{C_{des}}{280})^{0.8}$$

  Where:

  C_{des} = Design Tank Capacity, kg of hydrogen (from the Calculations table).

  The basis for the calculation is a tube trailer than contains 9 tubes. In the tube trailer tab where hydrogen is delivered as compressed gas, a trailer with 9 tubes and a maximum pressure of approximately 2700 psig can hold 280 kg of hydrogen. When increased by 50%, the footprint of the trailer is 180 m^2. The ratio of the capacity is raised to 0.8, which allows for some level of compressed gas storage tube stacking.

  If ***no*** is selected, then the user will need to enter the land required for the compressed gas storage system being analyzed.

- Land Required: If user opted not to use the H2A estimations for compressed gas system storage land requirement, the land required, in m^2, should be entered in this cell..

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of storage tanks.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Installed Capital Cost: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.7.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the compressed gas storage tubes are entered. The table is divided into two sections: labor, and the remainder of costs. Remember that the compressed gas storage tubes do not require any energy for operation, and thus the user does not need to enter any fuel/utility information. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: The user should enter the total labor-hours per year required to operate the compressed gas storage tubes.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.

- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.

- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the storage tanks.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom of the table.

5.7.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor and other O&M costs for the compressed gas storage tubes are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.8 Truck-Tube Delivery_2700 psi Tab

This tab is used to calculate the contribution to the delivered hydrogen cost for a current technology compressed gas trailer which is pulled by a tractor. According to industry experts, the typical operating pressure for a fully-loaded, current technology tube trailer is approximately 2,700 psig. A typical 9-tube trailer is shown in the picture below.

Figure 14. Picture of a current technology tube trailer (photo downloaded from NREL PhotoPix library).

5.8.1 Design Concept

One of the concerns when designing a truck-tube trailer component is that the truck will sit around idle. In this instance, the amount of hydrogen delivered by the component would be low, leading to a high cost. This tab was designed with this potential limitation in mind.

To maximize the usage of the truck, it is assumed that a single tractor can serve multiple forecourt stations. Because the trailers are assumed to be left at a forecourt station and used as onsite storage, a single truck will be moving many trailers around to the stations that it will serve. It is assumed that each trailer is refilled at the same terminal facility. The number of trailers for each tractor is calculated by considering the time required to empty the trailer at the forecourt station (depends on the forecourt station capacity) and the time required to deliver a full trailer and to return an empty trailer. The number of trailers required for this tab is usually going to be more than the number of stations served because there always needs to be a full trailer ready to be delivered when the tractor returns to the terminal with the empty trailer.

Based upon a maximum pressure of 2640 psig and a minimum (empty) pressure of 220 psig, a trailer with 9 pressure vessels/tubes can hold approximately 280 kg of hydrogen. Replacing a tube trailer more than one time a day may present logistical problems at the station. Therefore, the H2A delivery team recommends that the 2640 psig trailer modeled in this tab only be used for stations where the amount of hydrogen dispensed per day is less than the amount of hydrogen contained in one trailer.

5.8.2 Key Assumptions

- The number of trailers included (therefore the number of stations served) is optimized to maximize the usage of the tractor. In cases where more tractors are needed to meet the peak demand, additional capital is allocated for more tractors.

5.8.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Truck-Tube Trailer Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

5.8.4 Design Inputs

The design inputs table is used for entering values that determine the hydrogen capacity of a trailer. The first entry in the table, in cell B23, asks the user to determine whether he or she wants to calculate the capacity of a trailer based on maximum and minimum pressures and water volume. To select ***ye***s or ***no***, simply click on the arrow to the right of the cell. Once ***ye***s or ***no*** is selected, the "Design Input" for the cells that require input will have text.

If ***yes*** is selected, you are required to enter the following parameters:

- Tube Maximum Operating Pressure: Enter the maximum pressure that the storage tubes can accept.
- Tube Minimum Operating Pressure: Enter the pressure at which the tank is considered to be empty. Remember that this pressure will not be 14.7 psia because the tank is never completely emptied.
- Number of Tubes: Enter the number of hydrogen pressure tubes on a trailer. For example, a Super Jumbo trailer holds 9 tubes. There are space limitations on a typical trailer, and it is important to consider this fact when deciding on the number of tubes.
- Tube Water Volume: This value is the actual volume inside one of the hydrogen pressure tubes.
- Tube Operating Temperature: Enter the average temperature of the gas inside the hydrogen pressure tube.

If ***no*** is selected, you are only required to enter the number of tubes (described above) and the hydrogen capacity of the truck, in kg.

- Enter the Hydrogen Tube Trailer Capacity: Enter the total hydrogen capacity of the trailer, in kg of hydrogen.

5.8.5 Scenario Inputs

The entries in this table relate specifically to the set-up of a generic and simple delivery scenario. There are not any yes/no toggle switches, so all cells require input.

- Round Trip Distance: Enter the roundtrip distance, in km, between the delivery point and the origin.

- Average Hydrogen Station Demand: Enter the average daily hydrogen station demand, in kg/day.

- Peak Hydrogen Station Demand: Enter the peak daily hydrogen station demand, in kg/day. The number of tractors required for the specified inputs can be increased depending on whether a single tractor cannot meet the peak demand.

- Capacity Factor: This value is calculated by dividing the Average Hydrogen Station Demand by the Peak Hydrogen Station Demand.

- Total Time for Loading H2 into the Tube Trailer: Enter only the time the trailer is attached for filling. The time for maneuvering the trailer at the terminal, and attaching it to the refueling bay, is accounted for with another entry.

- Time to Pick-Up Trailer at the Terminal: Enter the time required to detach the trailer from the refueling bay, hook the trailer up to the truck and maneuvering around and exiting the terminal.

- Time to Drop-Off Trailer at the Terminal: Enter the time required to enter the terminal, maneuver around to the refueling bay, detaching the trailer from the truck, and hooking up the trailer to the equipment in the refueling bay.

- Time to Drop-Off Trailer at the Station: Enter the time required to remove the empty trailer and drop-off and hook-up the new trailer.

- Average Truck Speed: Enter the average truck speed considering that the truck will likely be traveling on both highways and city streets.

- Average Truck Gas Mileage: Enter the average gas mileage that the truck will get while moving empty and loaded trailers from the terminal to a forecourt station.

- Truck Yearly Availability: Enter the percentage of the year that the tractor will be available for use. It is necessary to consider maintenance downtime when determining the availability.

5.8.6 Calculations

The calculations in the table are used to determine several items, the most important of which are the amount of hydrogen processed by the tractor/compressed gas trailer(s) and the number of stations that will be served in order to maximize the use of the tractor.

- Truck Availability: This value is determined by multiplying the Truck Yearly Availability by the total hours in a year (8760 hr/year).
- Hydrogen Delivered Per Tube: The calculation used to determine the hydrogen delivered per tube depends on whether ***yes*** or ***no*** was selected in the Design Inputs table.
  - If ***yes*** is selected, the following formula is used:

    $$H_2(kg) = ZR\left(\frac{P_{\max}V_{tube} - P_{\min}V_{tube}}{T + 273.15}\right)$$

    Where:

    Z = Compressibility factor (evaluated a maximum or minimum pressure, as appropriate)
    R = Gas constant = 82.05 x 10^{-6} K.mol/atm.m^3
    P_{max} = Tube maximum operating pressure
    P_{min} = Tube minimum operating pressure
    V_{tube} = Tube water volume
    T = Tube operating temperature
  - If ***no*** is selected, the capacity entered is simply divided by the number of tubes entered.
- Number of Tubes: This value is read from the input in the Design Inputs table.
- Tube Trailer Delivered Hydrogen Capacity: This value is calculated by multiplying the Hydrogen Delivered Per Tube by the Number of Tubes.
- Total Trip Time: This value is calculated by summing the Total Time for Loading H2 into the Tube Trailer, the Time to Pick-Up Trailer at the Terminal, the Time to Drop-Off Trailer at the Terminal, the Time to Drop-Off Trailer at the Station and adding the result to the product of the Average Truck Speed and the Round Trip Distance.
- Maximum Number of Trips Per Day: This value is determined by dividing 24 (hours/day) by the Total Trip Time.
- Average Time to Empty Tube Trailer at Station: To calculate this number, the Tube Trailer Delivered Hydrogen Capacity is divided by the Average Hydrogen Station Demand.

- Number of Stations Served (assuming each trip is to a different station): Calculated by multiplying the Maximum Number of Trips Per Day and the Time to Empty Tube Trailer at Station.

- Number of Tube Trailers Required (based on the number of trips): To calculate this number, one is added to the Number of Stations Served because there will always be one trailer in transit. Additionally, an allotment has to be made for the terminal because there always has to be a filled trailer when the tractor returns. Therefore, the Total Time for Loading H2 into Tubes is divided by the Total Trip Time, and the result is added to the Number of Stations Served plus one.

- Number of Trips per Year: This value is calculated by multiplying the Maximum Number of Trips per Day by the Truck Availability.

- Truck Fuel Required per Trip: To obtain this value, the Round Trip Distance is divided by the Average Truck Gas Mileage.

- Net Hydrogen Delivered: The Number of Trips per Year is multiplied by the Tube Trailer Hydrogen Delivered Capacity to determine this number.

5.8.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.8.8 Capital Investment

This table is where the capital costs are entered. In this case, only two costs are required: the tractor cost and the trailer cost. The capital costs are entered in their specific rows in the second column of the table.

The tab allows entry of capital costs for the following items:

- Tractor: This component is the truck that pulls the trailer.

- Trailer: This component is the compressed gas trailer, including the pressure tubes and carriage to carry them.

- Loading/Unloading Equipment: This item includes additional equipment required to load and unload the hydrogen from the trailer, other than what might already be included in the trailer capital cost.

- Balance of Component: This item includes any other equipment that might be required for operation of a compressed gas truck trailer that has not already been included in the previous items.

It is important to note that the capital costs entered for the trailers and tractors are on a per unit basis. The Loading and Unloading Equipment and the Balance of Component, on the other hand, should be entered on a net basis.

The number of units is determined according to the following conventions:

- Tractor: The only reason that this number would not be 1 is if a single tractor can not meet the peak demand flowrate, assuming that it was simultaneously occurring at each station. Regardless, the value is determined by dividing th Peak Hydrogen Station Demand by the Average Hydrogen Station Demand, and then rounding the result up to the nearest integer.

- Trailers: The value shown for the number of trailers is transferred from the calculations block. The actual calculation for determining the number of stations is explained in the Calculations section for this tab.

The capital cost per unit is multiplied by the number of components (tractors and trailers, respectively) to determine the actual capital expended for each of these components. These numbers are then added to the Loading/Unloading Equipment and Balance of Component costs to determine the total capital cost.

5.8.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the compressed gas truck-trailer delivery unit are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: This value is calculated based on data from the Calculations table. The labor necessary is determined by multiplying the trip time by the number of trips per year.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to drive and load/unload the tractor trailer. It is assumed that the driver can also attach and detach the trailers at the forecourt station and the terminal.

- Percent of Labor Cost Allocated to Trailer: This item is entered by the user. Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the labor cost to the truck and another portion to the trailer. In most instances, the majority, if not all, of the labor costs should be allocated to the tractor.

For this tab, it is assumed that the only fuel required for the compressed gas truck-trailer is diesel fuel to operate the tractor. The first item in the fuel section is the fuel consumption, which is calculated in the Calculations table, and linked to this cell in the Operation and Maintenance table.

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total fuel cost is determined by multiplying either the user-input fuel cost or the H2A value by the Fuel Consumption per Trip and the Number of Trips per Year.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the compressed gas truck-trailer. The value needs to be entered on a $/km basis. This type of information can be obtained from organizations such as the American Trucking Association.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance per km cost by the total number of km driven in a year.

- Percentage of Insurance Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual insurance cost to the truck and another portion to the trailer. In most instances, the majority, if not all, of the insurance costs should be allocated to the tractor.

- Property Taxes: A percentage of the total capital investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the total capital investment by the property tax rate previously described.

- Percentage of Property Taxes Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the property tax cost to the truck and another portion to the trailer. In this case, the percentage is calculated by dividing the tractor portion of the total capital cost by the total capital cost.

- Licensing and Permits: The licensing and permits O&M costs needs to be entered on a $/km basis. This item includes all licensing and permit fees for operating the compressed gas truck-trailer. This type of information can be obtained from organizations such as the American Trucking Association.

- Licensing and Permits, annual: The annual licensing and permits cost is determined by multiplying the licensing cost per km by the total number of km driven in a year.

- Percentage of Licensing and Permits Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual licensing and permit costs to the truck and another portion to the trailer.

- Operating, Maintenance and Repairs: On a per km basis, the user needs to enter a cost for annual operating maintenance and repair items. This type of information can be obtained from organizations such as the American Trucking Association, and includes tire changes, oil changes, and other standard maintenance items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the per km cost by the total number of km driven in a year.

- Percentage of Operating, Maintenance and Repair Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual operating, maintenance and repair costs to the truck and another portion to the trailer. The majority of these costs should probably be assigned to the tractor.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Percentage of Overhead and G&A Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the overhead and G&A costs to the truck and another portion to the trailer. The costs are allocated the same as the labor costs.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

- Percentage of Other Fixed Operating Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the other fixed operating costs to the truck and another portion to the trailer.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.8.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the tractor and the trailers, respectively, are pooled together so that the hydrogen cost can be determined for each component. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.9 Truck-Tube Delivery_7000 psi Tab

This tab is used to calculate the contribution to the delivered hydrogen cost for a future technology compressed gas trailer which is pulled by a tractor. A composite tube trailer might have a maximum pressure of approximately 7,000 psig. The calculations in this tab assume that these this technology is developed and meets appropriate highway regulations.

As will be come obvious, this tab is very similar to the Truck-Tube Delivery_2700 psi tab. Therefore, much of the description in this section is taken from that tab.

5.9.1 Design Concept

One of the concerns when designing a truck-tube trailer component is that the truck will sit around idle. In this instance, the amount of hydrogen delivered by the component would be low, leading to a high cost. This tab was designed with this potential limitation in mind.

To maximize the usage of the truck, it is assumed that a single tractor can serve multiple forecourt stations. Because the trailers are assumed to be left at a forecourt station and used as onsite storage, a single truck will be moving many trailers around to the stations that it will serve. It is assumed that each trailer is refilled at the same terminal facility. The number of trailers for each tractor is calculated by considering the time required to empty the trailer at the forecourt station (depends on the forecourt station capacity) and the time required to deliver a full trailer and to return an empty trailer. The number of trailers required for this tab is usually going to be more than the number of stations served because there always needs to be a full trailer ready to be delivered when the tractor returns with the empty trailer.

Based upon a maximum pressure of 7000 psig and a minimum (empty) pressure of 220 psig, a trailer can almost 660 kg of hydrogen. Replacing a tube trailer more than one time a day may present logistical problems at the station. Therefore, the H2A delivery team recommends that the 7000 psig trailer modeled in this tab only be used for stations where the amount of hydrogen dispensed per day is less than the amount of hydrogen contained in one trailer.

5.9.2 Key Assumptions

- The number of trailers included (therefore the number of stations served) is optimized to maximize the usage of the tractor. In cases where more tractors are needed to meet the peak demand, additional capital is allocated for more tractors.

5.9.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Truck-Tube Trailer Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

2. No capital costs are entered.

5.9.4 Design Inputs

The design inputs table is used for entering values that determine the hydrogen capacity of a trailer. The first entry in the table, in cell B23, asks the user to determine whether he or she wants to calculate the capacity of a trailer based on maximum and minimum pressures and water volume. To select ***ye***s or ***no***, simply click on the arrow to the right of the cell. Once ***ye***s or ***no*** is selected, the "Design Input" for the cells that require input will have text.

If ***yes*** is selected, you are required to enter the following parameters:

- Tube Maximum Operating Pressure: Enter the maximum pressure that the storage tubes can accept.

- Tube Minimum Operating Pressure: Enter the pressure at which the tank is considered to be empty. Remember that this pressure will not be 14.7 psia because the tank is never completely emptied.

- Number of Tubes: Enter the number of hydrogen pressure tubes on a trailer. For example, a Super Jumbo trailer holds 9 tubes. There are space limitations on a typical trailer, and it is important to consider this fact when deciding on the number of tubes.

- Tube Water Volume: This value is the actual volume inside one of the hydrogen pressure tubes.

- Tube Operating Temperature: Enter the average temperature of the gas inside the hydrogen pressure tube.

If ***no*** is selected, you are only required to enter the number of tubes (described above) and the hydrogen capacity of the truck, in kg.

- Enter the Hydrogen Tube Trailer Capacity: Enter the total hydrogen capacity of the trailer, in kg of hydrogen.

5.9.5 Scenario Inputs

The entries in this table relate specifically to the set-up of a generic and simple delivery scenario. There are not any yes/no toggle switches, so all cells require input.

- Round Trip Distance: Enter the roundtrip distance, in km, between the delivery point and the origin.

- Average Hydrogen Station Demand: Enter the average daily hydrogen station demand, in kg/day.

- Peak Hydrogen Station Demand: Enter the peak daily hydrogen station demand, in kg/day. The number of tractors required for the specified inputs can be increased depending on whether a single tractor cannot meet the peak demand.

- Capacity Factor: This value is calculated by dividing the Average Hydrogen Station Demand by the Peak Hydrogen Station Demand.

- Total Time for Loading H2 into the Tube Trailer: Enter only the time the trailer is attached for filling. The time for maneuvering the trailer at the terminal, and attaching it to the refueling bay, is accounted for with another entry.

- Time to Pick-Up Trailer at the Terminal: Enter the time required to detach the trailer from the refueling bay, hook the trailer up to the truck and maneuvering around and exiting the terminal.

- Time to Drop-Off Trailer at the Terminal: Enter the time required to enter the terminal, maneuver around to the refueling bay, detaching the trailer from the truck, and hooking up the trailer to the equipment in the refueling bay.

- Time to Drop-Off Trailer at the Station: Enter the time required to remove the empty trailer and drop-off and hook-up the new trailer.

- Average Truck Speed: Enter the average truck speed considering that the truck will likely be traveling on both highways and city streets.

- Average Truck Gas Mileage: Enter the average gas mileage that the truck will get while moving empty and loaded trailers from the terminal to a forecourt station.

- Truck Yearly Availability: Enter the percentage of the year that the tractor will be available for use. It is necessary to consider maintenance downtime when determining the availability.

5.9.6 Calculations

The calculations in the table are used to determine several items, the most important of which are the amount of hydrogen processed by the tractor/compressed gas trailer(s) and the number of stations that will be served in order to maximize the use of the tractor.

- Truck Availability: This value is determined by multiplying the Truck Yearly Availability by the total hours in a year (8760 hr/year).

- Hydrogen Delivered Per Tube: The calculation used to determine the hydrogen delivered per tube depends on whether ***yes*** or ***no*** was selected in the Design Inputs table.

    - If ***yes*** is selected, the following formula is used:

$$H_2(kg) = ZR\left(\frac{P_{\max}V_{tube} - P_{\min}V_{tube}}{T + 273.15}\right)$$

    Where:

    Z = Compressibility factor (evaluated a maximum or minimum pressure, as appropriate)

R = Gas constant = 82.05 x 10^{-6} K.mol/atm.m^3
P_{max} = Tube maximum operating pressure
P_{min} = Tube minimum operating pressure
V_{tube} = Tube water volume
T = Tube operating temperature

- If ***no*** is selected, the capacity entered is simply divided by the number of tubes entered.

- Number of Tubes: This value is read from the input in the Design Inputs table.

- Tube Trailer Delivered Hydrogen Capacity: This value is calculated by multiplying the Hydrogen Delivered Per Tube by the Number of Tubes.

- Total Trip Time: This value is calculated by summing the Total Time for Loading H2 into the Tube Trailer, the Time to Pick-Up Trailer at the Terminal, the Time to Drop-Off Trailer at the Terminal, the Time to Drop-Off Trailer at the Station and adding the result to the product of the Average Truck Speed and the Round Trip Distance.

- Maximum Number of Trips Per Day: This value is determined by dividing 24 (hours/day) by the Total Trip Time.

- Average Time to Empty Tube Trailer at Station: To calculate this number, the Tube Trailer Delivered Hydrogen Capacity is divided by the Average Hydrogen Station Demand.

- Number of Stations Served (assuming each trip is to a different station): Calculated by multiplying the Maximum Number of Trips Per Day and the Time to Empty Tube Trailer at Station.

- Number of Tube Trailers Required (based on the number of trips): To calculate this number, one is added to the Number of Stations Served because there will always be one trailer in transit. Additionally, an allotment has to be made for the terminal because there always has to be a filled trailer when the tractor returns. Therefore, the Total Time for Loading H2 into Tubes is divided by the Total Trip Time, and the result is to the Number of Stations Served plus one.

- Number of Trips per Year: This value is calculated by multiplying the Maximum Number of Trips per Day by the Truck Availability.

- Truck Fuel Required per Trip: To obtain this value, the Round Trip Distance is divided by the Average Truck Gas Mileage.

- Net Hydrogen Delivered: The Number of Trips per Year is multiplied by the Tube Trailer Hydrogen Delivered Capacity to determine this number.

5.9.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.9.8 Capital Investment

This table is where the capital costs are entered. In this case, only two costs are required: the tractor cost and the trailer cost. The capital costs are entered in their specific rows in the second column of the table.

The tab allows entry of capital costs for the following items:

- Tractor: This component is the truck that pulls the trailer.
- Trailer: This component is the compressed gas trailer, including the pressure tubes and carriage.
- Loading/Unloading Equipment: This item includes additional equipment required to load and unload the hydrogen from the trailer, other than what might already be included in the trailer capital cost.
- Balance of Component: This item includes any other equipment that might be required for operation of a compressed gas truck trailer that has not already been included in the previous items.

It is important to note that the capital costs entered for the trailers and tractors are on a per unit basis. The Loading and Unloading Equipment and the Balance of Component, on the other hand, should be entered on a net basis.

The number of units is determined according to the following conventions:

- Tractor: The only reason that this number would not be 1 is if a single tractor can not meet the peak demand flowrate, assuming that it was simultaneously occurring at each station. Regardless, the value is determined by dividing th Peak Hydrogen Station Demand by the Average Hydrogen Station Demand, and then rounding the result up to the nearest integer.
- Trailers: The value shown for the number of trailers is transferred from the calculations block. The actual calculation for determining the number of stations is explained in the Calculations section for this tab.

The capital cost per unit is multiplied by the number of components (tractors and trailers, respectively) to determine the actual capital expended for each of these components. These numbers are then added to the Loading/Unloading Equipment and Balance of Component costs to determine the total capital cost.

5.9.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the compressed gas truck-trailer delivery unit are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: This value is calculated based on data from the Calculations table. The labor necessary is determined by multiplying the trip time by the number of trips per year.
- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to drive and load/unload the tractor trailer. It is assumed that the driver can also attach and detach the trailers at the forecourt station and the terminal.
- Percent of Labor Cost Allocated to Trailer: This item is entered by the user. Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the labor cost to the truck and another portion to the trailer. In most instances, the majority, if not all, of the labor costs should be allocated to the tractor.

For this tab, it is assumed that the only fuel required for the compressed gas truck-trailer is diesel fuel to operate the tractor. The first item in the fuel section is the fuel consumption, which is calculated in the Calculations table, and linked to this cell in the Operation and Maintenance table.

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total fuel cost is determined by multiplying either the user-input fuel cost or the H2A value by the Fuel Consumption per Trip and the Number of Trips per Year.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the compressed gas truck-trailer. The value needs to be entered on a $/km basis. This type of information can be obtained from organizations such as the American Trucking Association.
- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance per km cost by the total number of km driven in a year.
- Percentage of Insurance Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual insurance cost to the truck and another portion to the trailer. In most instances, the majority, if not all, of the insurance costs should be allocated to the tractor.
- Property Taxes: A percentage of the total capital investment should be allocated for annual property taxes.
- Property Taxes, annual: The annual property taxes are calculated by multiplying the total capital investment by the property tax rate previously described.

- Percentage of Property Taxes Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the property tax cost to the truck and another portion to the trailer. In this case, the percentage is calculated by dividing the tractor portion of the total capital cost by the total capital cost.

- Licensing and Permits: The licensing and permits O&M costs needs to be entered on a $/km basis. This item includes all licensing and permit fees for operating the compressed gas truck-trailer. This type of information can be obtained from organizations such as the American Trucking Association.

- Licensing and Permits, annual: The annual licensing and permits cost is determined by multiplying the licensing cost per km by the total number of km driven in a year.

- Percentage of Licensing and Permits Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual licensing and permit costs to the truck and another portion to the trailer.

- Operating, Maintenance and Repairs: On a per km basis, the user needs to enter a cost for annual operating maintenance and repair items. This type of information can be obtained from organizations such as the American Trucking Association, and includes tire changes, oil changes, and other standard maintenance items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the per km cost by the total number of km driven in a year.

- Percentage of Operating, Maintenance and Repair Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual operating, maintenance and repair costs to the truck and another portion to the trailer. The majority of these costs should probably be assigned to the tractor.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Percentage of Overhead and G&A Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the overhead and G&A costs to the truck and another portion to the trailer. The costs are allocated the same as the labor costs.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

- Percentage of Other Fixed Operating Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the other fixed operating costs to the truck and another portion to the trailer.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.9.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the tractor and the trailers, respectively, are pooled together so that the hydrogen cost can be determined for each component. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.10 Compressed Gas Hydrogen Storage Tubes

This tab is used to calculate the contribution to the delivered hydrogen cost for larger-scale compressed gas storage tubes. The scale of storage that this tab is designed to handle is on the terminal level. For example, a terminal operating with compressed gas and fed by a pipeline will need to be able to store a certain amount of hydrogen on-site to handle demand surges or pipeline outages. The compressed gas storage tubes could also be located at a central production facility, and serve the same purpose as at the terminal; to provide extra capacity in the course of a facility shut-down.

Figure 15. An array of compressed gas storage tubes (photo is credited to Linde Corp.)

5.10.1 Design Concept

This tab is used for the design and cost of a central, large-scale compressed gas storage system. At this stage, compressed gas storage typically involves long, metallic pressure tubes (such as those shown in Figure 15). This tab has the flexibility to handle different types of compressed gas tubes, such carbon-wrapped units which could have a larger volume and also hold higher pressures than their metallic counterparts.

In a typical gas storage operation, the storage tubes are not allowed to completely empty. In other words, the storage tubes are considered to be empty when the pressure drops to a certain level. This tab is designed with the same philosophy. The user can enter a maximum storage pressure, and then a minimum storage pressure. The calculations will then determine the actual amount of hydrogen stored.

5.10.2 Key Assumptions

- No energy is required to operate the storage tubes. A compressor that may be required to get the hydrogen to the storage pressure can be sized, and its energy consumption determined, using the compressor tab.
- The storage system is assumed to be filled and emptied continuously during the year. Thus, the amount of hydrogen delivered from this component is calculated by multiplying the Average Daily Demand from the storage system by 365 days/year.

5.10.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Compressed Gas H2 Storage Tubes Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

2. No capital costs are entered.

5.10.4 Design Inputs

The design inputs table is used for entering values to determine how much hydrogen will be stored in the compressed gas storage tubes. This table contains yes/no toggle switches to enhance the flexibility of the model. The user has the option to size the storage system based on an Average Demand on the storage system, the maximum and minimum pressures and the number of days of storage. Or, the user can simply enter the size of a storage system where the capacity is known.

If ***yes*** is selected by the user for the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Capacity?", then the following inputs are required.

- Tank Maximum Pressure: The user should enter the maximum pressure of hydrogen that can be stored in the compressed gas storage tubes. Please note that this is not a design pressure. This is the maximum operating pressure of hydrogen that can be stored.

- Tank Minimum Pressure: The user should enter the minimum pressure of hydrogen that can be stored in the compressed gas storage tubes. As mentioned previously, the tanks are usually not completely emptied when they are considered depleted, and ready for a recharge of hydrogen.

- Tank Operating Temperature: Enter the temperature of the gaseous hydrogen held in this compressed gas storage system.

- Average Hydrogen Demand: Enter the average amount of hydrogen that the system the storage is supplying needs to provide.

If ***no*** is selected for the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Capacity?", then input is required only in the following cell.

- Enter the Capacity of the Compressed Gas Storage System: The user should enter capacity, in kg, of the compressed gas storage system that they would like to analyze. If this option is used, it is assumed that the user has considered minimum and maximum pressure in the vessel.

5.10.5 Scenario Inputs

- Number of Days of Storage: If the user answered ***yes*** to the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Capacity?", then the user needs to enter the number of days of storage desired. This input is multiplied by the average hydrogen demand (in conjunction with maximum and minimum pressures) to determined the size of the desired compressed gas storage system.

5.10.6 Calculations

- Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual. The compressibility factor is evaluated at the maximum pressure and the operating temperature.

- Design Tank Useable Capacity: The value calculated in this cell depends on how the user answered the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Capacity?".

  If the user entered ***yes***, this value is calculated by multiplying the Number of Days of Storage by the Average Hydrogen Demand. It is important to note that this calculation does not take into account the maximum and minimum pressure requirements.

  If the user entered ***no***, the Capacity of the Compressed Gas Storage System, entered in the Design Inputs Table, is fed to this cell.

- Calculated Useable Tank Capacity: The value calculated in this cell depends on how the user answered the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Capacity?".

  If the user entered ***yes***, this value is used to determine the actual size of the compressed gas storage system. There will be some gas left in the storage system when it is considered empty based upon the minimum pressure entered in the Design Inputs table.. Therefore, in order to meet the Average Demand and Number of Days of Storage requirements, the compressed gas storage will need to be oversized. To calculate the percentage of the tank that is "useable", the following formula is used.

$$Frac_{use} = \frac{\frac{P_{\max}}{Z} - P_{\min}}{\frac{P_{\max}}{Z}}$$

Where:

P_{max} = maximum pressure in storage tubes (from Design Inputs table)
P_{min} = minimum pressure in storage tubes (from Design Inputs table)
Z = compressibility factor.

If the user entered ***no***, then "N/A" appears because it is assumed that the user considered maximum and minimum pressure constraints when putting a value for the Capacity of the Compressed Gas Storage System.

- Design Tank Capacity: The value calculated in this cell depends on how the user answered the question "Size Compressed Gas Storage Based on Storage Time and Average Hydrogen Capacity?".

  If the user entered ***yes***, this value is calculated by dividing the Design Tank Useable Capacity by the Calculated Useable Tank Capacity. The result of this calculation is the capacity that the storage tubes will have to contain in order to meet the maximum and minimum pressure requirements.

  If the user entered ***no***, the Capacity of the Compressed Gas Storage System, entered in the Design Inputs Table, is fed to this cell.

- Tank Volume: The result of the calculation used in this cell is for informational purposes only. The volume is calculated according to the following equation.

$$V = \frac{C_{des} Z T_{oper} R}{P_{\max}}$$

  Where all the variables have been defined previously in this section except:

  C_{des} = Design Tank Capacity, converted to moles of hydrogen
  T_{oper} = operating temperature, converted to K (from Design Inputs table)
  R = gas constant, 8.2x10-5 psi/mol.K.

- Hydrogen Dispensed: This value is equivalent to the Average Hydrogen Demand.

- Net Hydrogen Delivered: This value is calculated by multiplying the Hydrogen Dispensed by 365 (days/yr).

5.10.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.10.8 Capital Investment

This table is where the capital costs for the compressed gas storage tubes are entered.

The H2A Delivery team has developed a cost function that can estimate the capital cost of a compressed gas storage system. The cost is based on a value of \$818/kg of hydrogen stored, which was obtained from the H2A Forecourt team. The cost figure represents a tank that can hold 6,250 psi of hydrogen. The capacity of the storage system is raised to a 0.8 exponent to account for economies of scale. Additionally, the value of \$818/kg of hydrogen is not installed, the final number is multiplied by 1.1 (10% installation factor) to determine the installed cost.

The specific entries for this table are described below.

- Use the H2A Compressed Gas Storage Costs: The entry for this cell uses a yes/no toggle switch. If ***yes*** is selected, then:

  - The H2A compressed gas storage cost function, described above, is used for the compressor capital cost. Not other entry is required in the Capital Cost table.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Compressed Gas Storage Tank: The calculation in the "Compressed Gas Storage System Size (kg)" column reads the Design Tank Capacity of the compressed gas storage system that was calculated in the Calculations table. The specific entries required in this row depend on whether the user opted to use the H2A Compressed Gas Storage costs. If ***yes*** was selected, then the value in the "Installed Costs from H2A Data" is filled.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Balance of Component: This item includes any other equipment that might be required for operation of a compressed gas storage tube system that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment. The following items are either calculated, or require entry in this table.

- Use H2A Estimation for Compressed Gas Storage System size: The user is required to select yes/no with the toggle switch. If ***yes*** is selected, a function to determine the amount of land required for the compressed gas storage system is used. This function is shown below.

  $$Land = 180(\frac{C_{des}}{280})^{0.8}$$

  Where:

  C_{des} = Design Tank Capacity, kg of hydrogen (from the Calculations table).

  The basis for the calculation is a tube trailer than contains 9 tubes. In the tube trailer tab where hydrogen is delivered as compressed gas, a trailer with 9 tubes and a maximum pressure of approximately 2700 psig can hold 280 kg of hydrogen. When increased by 50%, the footprint of the trailer is 180 m^2. The ratio of the capacity is raised to 0.8, which allows for some level of compressed gas storage tube stacking.

  If ***no*** is selected, then the user will need to enter the land required for the compressed gas storage system being analyzed.

- Land Required: If user opted not to use the H2A estimations for compressed gas system storage land requirement, the land required, in m^2, should be entered in this cell..

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of these storage tanks.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Installed Capital Cost: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.10.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the compressed gas storage tubes are entered. The table is divided into two sections: labor, and the remainder of costs. Remember that the compressed gas storage tubes do not require any energy for operation, and thus the user does not need to enter any fuel/utility information. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: The user should enter the total labor-hours per year required to operate the compressed gas storage tubes.
- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.
- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.
- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.
- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.
- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.
- Licensing and Permits: The licensing and permits O&M costs need to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the storage tanks.
- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.
- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.
- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.
- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom of the table.

5.10.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor and other O&M costs for the compressed gas storage tubes are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.11 Truck_LH2 Delivery Tab

This tab is used to calculate the contribution to the delivered hydrogen cost for a cryogenic trailer carrying liquid hydrogen which is pulled by a tractor. A cryogenic trailer, such as than show in Figure 16, can hold approximately 3,900 kg of liquid hydrogen when fully loaded, according to members of the H2A Key Industrial Collaborators.

Figure 16. A tractor-trailer that can deliver liquid hydrogen to a forecourt station (photo downloaded from the Praxair website).

5.11.1 Design Concept

This tab is designed differently from the Truck-Tube Delivery tabs. The primary difference is that the component analyzed for the Truck_LH2 tab includes only combinations of one trailer and one tractor. The H2A Key Industrial Collaborators described most of their liquid delivery tractor trailers as a single component that is rarely separated. An additional difference between this liquid H2 truck delivery tab and the compressed gas truck tab is that the trailer is not used as storage at the forecourt facility.

The liquid trailer is filled with liquid hydrogen at a terminal, and then sets off to deliver to forecourt stations. According to the H2A Key Industrial Collaborators, these liquid trucks rarely make more than three stops on their journey. Therefore, the user can opt for the tractor trailer to make one, two or three deliveries during a single trip. The model is set-up with a macro that determines the amount of liquid hydrogen delivered on each stop based on boil-off during loading/unloading and during travel.

A typical current technology liquid hydrogen trailer can hold up to 3,900 kg of hydrogen. The macro assumes that an equivalent amount of hydrogen will be delivered to each stop along the route. This simplification helps to minimize the complexity of the boil-off calculations, which are based on capacity and delivery distance.

5.11.2 Key Assumptions

One combination tractor-trailer is used to deliver the liquid hydrogen, and can make one, two or three stops. The tab is designed such that the same amount of hydrogen is delivered to each of the forecourt stations. Only the capital costs will be affected if more than one tractor/trailer combination is necessary to meet the peak demand,

- The stations and the terminal are equidistant from one another. Thus, if the total delivery distance is 120 km, and there are 2 deliveries, the first station is 40 km from the terminal, and he second station is 40 km from the first station as well as 40 km from the terminal.

- The same amount of hydrogen is delivered to each station.

5.11.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Truck-LH2 Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. The data for the number of stops per trip has been changed, but the button that runs the macro has not been pushed.

2. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

3. No capital costs are entered.

5.11.4 Design Inputs

The design inputs are used for entering values to determine the hydrogen design capacity of a trailer. There are not any yes/no toggle switches, so all cells require input. The items included in this table are described below.

- Tank Water Volume: This value is the actual volume inside the liquid hydrogen storage container.

- Tank Loading Losses: This value accounts for the amount of liquid hydrogen that is lost during the loading of the trailer. The value needs to be entered as a percent of the total liquid hydrogen trailer capacity. If a recovery system is used at the terminal, this percent lost should be zero.

- Tank Unloading Losses: This value accounts for the amount of liquid hydrogen that is lost during the unloading of the trailer during a stop. The value needs to be entered as a percent of the total liquid hydrogen trailer capacity.

- Tank Boil-off Rate: During transport, a portion of the liquid hydrogen will boil-off and be vented through a relief value on the trailer. This value should be entered as a percentage loss per day, based on the total volume of the trailer.

5.11.5 Scenario Inputs

The entries in this table relate specifically to the set-up of a generic and simple delivery scenario. There are not any yes/no toggle switches, so all cells require input.

- Tank Useable Capacity: The trailer needs to be kept cold, even when returning to the terminal, in order to minimize losses. Therefore, it can never be completely emptied. This value, entered as a percentage of total capacity, quantifies the amount of liquid hydrogen that can actually be dispensed from a liquid hydrogen trailer.

- Round Trip Distance: Enter the roundtrip distance, in km, between the delivery point and the origin.

- Average Hydrogen Station Demand: Enter the average daily hydrogen station demand, in kg/day.

- Peak Hydrogen Station Demand: Enter the peak daily hydrogen station demand, in kg/day. The number of tractors required for the specified inputs can be increased depending on whether a single tractor cannot meet the peak demand.

- Capacity Factor: This value is calculated by dividing the Average Hydrogen Station Demand by the Peak Hydrogen Station Demand.

- Number of Stations per Trip: The value is entered into this cell using the pull-down menu at to the right of the cell. The user can enter one, two or three stations (stops) per trip. When this value is changed, it is imperative that the user hit the macro button (described later) before looking at the final results.

- Total Time to Load Truck: Enter the time the trailer is at the terminal. The time for maneuvering the trailer at the terminal, and attaching it to the refueling bay, should be included in this entry.

- Total Time to Unload Truck at each Station: Enter the time required to deliver the specified amount of liquid hydrogen. Include time that is required for connecting and disconnecting to the transfer system, and time used for maneuvering the truck.

- Average Truck Speed: Enter the average truck speed considering that the truck will likely be traveling on both highways and city streets.

- Average Truck Gas Mileage: Enter the average gas mileage that the truck will get while moving empty and loaded trailers from the terminal to a forecourt station.

- Truck Yearly Availability: Enter the percentage of the year that the tractor will be available for use. It is necessary to consider maintenance downtime when determining the availability.

5.11.6 Calculations

Because hydrogen losses are specified as a function of the volume of liquid hydrogen in the trailer, the calculation of the amount of hydrogen delivered by a given trailer is somewhat complex. For example, multiplying the total initial amount of hydrogen in the trailer by the Total Unloading Losses and the number of stops would not yield the proper amount of hydrogen lost because the amount of hydrogen in the trailer at the first stop is reduced by boil-off losses during the journey, and the amount of hydrogen in the trailer at the second stop is reduced by a delivery and further boil-off losses.

To handle this situation, an iterative calculator was developed. The iterations are limited by the number of deliveries selected (in the model, the maximum number of deliveries is 3). The table where the calculations are completed is located at the bottom of the spreadsheet (below the Economic Calculations table), and shown in Figure 14. No input is required in this calculation table, as the parameters are pulled from inputs in the Component Design and Scenario tables.

Calculation of Hydrogen Delivered to Each Station						
Stops	Hydrogen from Previous Station (kg)	Hydrogen Boil-off Losses During Delivery to Station (kg)	Hydrogen Unloading Losses (kg)	Hydrogen Delivered (kg)	Hydrogen Boil-off Losses During Unloading at Station (kg)	Hydrogen Remaining (kg)
Departure from Terminal	4342.14					4342.14
1	4342.14	147	248.44	3891	151	0.00
2	0.00	0.00	0.00	0	0.00	0.00
3	0.00	0.00	0.00	0	0.00	0.00

Figure 14. Table in the LH2 Truck tab where the amount of hydrogen delivered to each station is calculated.

Each row, except the first, corresponds to a truck leaving the previous station/terminal, delivering a set amount of liquid hydrogen, and the leaving the specified station. For example, in the second row of Figure 14 (stop #1), the amount of hydrogen from the terminal is first reduced by boil-off losses during delivery, then by unloading losses, then by a delivery, and finally from boil-off during unloading. The amount of hydrogen remaining after the first drop is then forwarded to the next row.

The first number that is calculated, shown in the row titled "Departure from Terminal" and the column with the heading "Hydrogen from Previous Station (kg)" is the amount of hydrogen that is loaded on the trailer when it leaves the terminal. The equation for calculating this value is:

$$H2(kg) = V_{\tan k} \rho_{LH2} A_{LH2truck}$$

Where:

V_{tank} = water volume of the trailer (entered in the Design Inputs table)
ρ_{LH2} = density of liquid hydrogen (taken from the Physical Properties tab)
$A_{LH2Truck}$ = availability of the liquid truck (taken from the Scenario table).

The result of this formula is transferred to the "Hydrogen from Previous Station (kg)" entry for stop #1 because it represents the amount of hydrogen in the tanker when it leaves the previous station (the terminal in this case). The next calculation determines the amount of boil-off losses during delivery to the station. The equation for calculating boil-off during the delivery is:

$$H_{2,boil-off} = H_{2,prev} B_r T$$

Where:

$H_{2,prev}$ = hydrogen in trailer from previous station/terminal
B_r = boil-off rate, %/day (taken from the Design Inputs table)
T = travel time, in days.

In this first leg the travel time is defined as:

$$T = \frac{D_{RT}}{24(1+N_{st})S_{truck}}$$

Where:

D_{RT} = roundtrip distance (taken from Scenario table)
N_{st} = number of deliveries (taken from the Scenario table)
S_{truck} = average speed of the truck (taken from the Scenario table).

The next value calculated, in the column entitled "Hydrogen Unloading Losses", is the amount of hydrogen that is lost during unloading. The equation for this calculation is:

$$H_{2,loss,unload} = U_{loss}(H_{2,prev} - H_{2,boil-off,del})$$

Where:

U_{loss} = percent of hydrogen lost during unloading (taken from Design Inputs table)
$H_{2,prev}$ = hydrogen in trailer from previous station/terminal
$H_{2,boil-off,del}$ = hydrogen lost to boil-off during delivery to station (calculated in previous cell)

The value for "Hydrogen Delivered (kg)" is calculated using a macro. The macro is activated by pushing the button located to the right of the Calculations table. In general terms, the macro ensures that there is no deliverable hydrogen left in the trailer when it returns to the terminal by varying the amount of hydrogen delivered to each station. It is important to remember that the model assumes that the same amount of hydrogen is delivered to each station.

The "Hydrogen Boil-off Losses During Unloading" is calculated using a formula similar to that for the Hydrogen Boil-off Losses During Delivery. The difference is the value that is used for the hydrogen content in the trailer. In this instance, the following formula is used to calculate $H_{2,prev}$ shown in the equation above:

$$H_{2,unload,boil-off} = \left(H_{2,prev} - H_{2,boil-off,del} - \left(\frac{H_{2,unload} + H_{2,loss,unload}}{2} \right) \right) \left(B_r T_{unload} \right)$$

Where all terms have been defined previously except:

$H_{2,prev}$ = hydrogen in trailer from previous station/terminal
$H_{2,boil\text{-}off,del}$ = hydrogen lost to boil-off during delivery to station (calculated previously)
$H_{2,unload}$ = hydrogen delivered to station (calculated in macro)
$H_{2,loss,unload}$ = hydrogen lost during unloading at station (calculated previously)
T_{unload} = time to unload hydrogen in days (based on data from the Scenario Table).

Finally, the amount of hydrogen remaining in the trailer when it leaves the station is calculated. The cell heading for this calculation is "Hydrogen Remaining (kg)". The formula for determining this value is:

$$H_{2,rem} = H_{2,prev} - H_{2,boil-off,del} - H_{2,unload} - H_{2,loss,unload} - H_{2,unload,boil-off}$$

Where all terms have been defined previously, except:

$H_{2,unload,boil\text{-}off}$ = hydrogen lost to boil-off during unloading (calculated previously).

These calculations repeat for each station per the users input in the Scenario table.

One final note on the calculations just described. If the user changes a particular variable that ends up changing the amount of hydrogen that will be delivered to each station, an error message appears in the area between the Calculation Outputs table and the Truck-LH2 Design Inputs table that alerts the user that the button will need to be pushed.

The calculations that appear in the Calculations Table are described below.

- <u>Truck Availability</u>: This value is determined by multiplying the Truck Yearly Availability by the total days in a year (365 hr/year).
- <u>Net Hydrogen Delivered per Trip</u>: This value is calculated by taking the sum of the values entered for the amount of hydrogen delivered to each station (see previous discussion of the "Calculation of Hydrogen Delivered to Each Station" table).
- <u>Net Hydrogen Delivered per Stop:</u> This value is determined by dividing the Net Hydrogen Delivered per Trip by the number of stations.
- <u>Total Trip Time</u>: This value is calculated by summing the Total Time to Load Truck at the terminal, the product of the Number of Stations per Trip and the Total Time to Unload Truck at each Station and the result of dividing Average Truck Speed and the Round Trip Distance.
- <u>Days Between Deliveries</u>: To calculate this number, Net Hydrogen Delivered per Stop is divided by the Average Hydrogen Station Demand.
- <u>Number of Trips per Year</u>: This value is calculated by dividing the Truck Availability by the Days Between Deliveries.
- <u>Maximum Trips per Day</u>: This value is calculated by dividing 24 hrs/day by the Total Trip Time.

- Truck Fuel Required per Trip: To obtain this value, the Round Trip Distance is divided by the Average Truck Gas Mileage.

- Net Hydrogen Delivered: The Number of Trips per Year is multiplied by the Net Hydrogen Delivered per Trip to determine this number. The losses and availability are taken into account by the Net Hydrogen Delivered per Trip calculation, and therefore do not appear in this calculation.

5.11.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.11.8 Capital Investment

This table is where the capital costs are entered. In this case, only two costs are required: the tractor cost and the trailer cost. The capital costs are entered in their specific rows in the second column of the table.

The tab allows entry of capital costs for the following items:

- Tractor: This component is the truck that pulls the trailer.

- Trailer: This component is the liquid hydrogen trailer, including the carriage and the cryogenic tank.

- Loading/Unloading Equipment: This item includes additional equipment required to load and unload the hydrogen from the trailer, other than what might already be included in the trailer capital cost.

- Balance of Component: This item includes any other equipment that might be required for operation of a liquid hydrogen truck and trailer that has not already been included in the previous items.

It is important to note that the capital costs entered for the trailers and tractors are on a per unit basis. The Loading and Unloading Equipment and the Balance of Component, on the other hand, should be entered on a net basis.

The number of units is determined according to the following conventions:

- Tractor: The only reason that this number would not be 1 is if a single tractor/trailer combination can not meet the peak demand flowrate. The formula for determining the number of tractors, and thus trailers, required to meet the peak demand flowrate is:

$$N_{trucks} = \frac{H2_{del,year}}{\frac{365 T_{\max}}{H2_{del,trip}} \frac{D_{avg}}{D_{peak}}}$$

Where:

N_{trucks} = the number of tractor/trailer combinations required
$H2_{del,year}$ = net hydrogen delivered per year (calculated in Calculations table)
D_{avg} = average hydrogen station demand (taken from the Scenario table)
D_{peak} = peak hydrogen station demand (taken from the Scenario table)
T_{max} = maximum trips per day (calculated in Calculations table)
$H2_{del,trip}$ = net hydrogen delivered per trip (calculated in Calculations table)

- Trailers: Because the tractors and trailers come as packaged units, the same formula shown above is used to calculate the number of trailers required.

5.11.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the liquid hydrogen truck delivery unit are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: This value is calculated based on data from the Calculations table. The labor necessary is determined by multiplying the Total Trip Time by the Number of Trips per Year.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to drive and load/unload the tractor trailer. It is assumed that the driver can also attach and detach the trailers at the terminal.

- Percent of Labor Cost Allocated to Trailer: This item is entered by the user. Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the labor cost to the truck and another portion to the trailer. In most instances, the majority, if not all, of the labor costs should be allocated to the tractor.

For this tab, it is assumed that the only fuel required for the liquid hydrogen truck is diesel fuel to operate the tractor. The first item is the fuel section is the fuel consumptions, which is calculated in the Calculations table, and linked to this cell in the Operation and Maintenance table.

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total fuel cost is determined by multiplying either the user-input fuel cost or the H2A value by the Fuel Consumption per Trip and the Number of Trips per Year.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the compressed gas truck-trailer. The value needs to be entered on a $/km basis. This type of information can be obtained from organizations such as the American Trucking Association.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance per km cost by the total number of km driven in a year.

- Percentage of Insurance Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual insurance cost to the truck and another portion to the trailer. In most instances, the majority, if not all, of the insurance costs should be allocated to the tractor.

- Property Taxes: A percentage of the total capital investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the total capital investment by the property tax rate previously described.

- Percentage of Property Taxes Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the property tax cost to the truck and another portion to the trailer. In this case, the percentage is calculated by dividing the tractor portion of the total capital cost by the total capital cost.

- Licensing and Permits: The licensing and permits O&M costs needs to be entered on a $/km basis. This item includes all licensing and permit fees for operating the liquid hydrogen truck-trailer. This type of information can be obtained from organizations such as the American Trucking Association.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost per km by the total number of km driven in a year.

- Percentage of Licensing and Permits Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual licensing and permit costs to the truck and another portion to the trailer.

- Operating, Maintenance and Repairs: On a per km basis, the user needs to enter a cost for annual operating maintenance and repair items. This type of information can be obtained from organizations such as the American Trucking Association, and includes tire changes, oil changes, and other standard maintenance items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the per km cost by the total number of km driven in a year.

- Percentage of Operating, Maintenance and Repair Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the annual operating, maintenance and repair costs to the truck and another portion to the trailer. The majority of these costs should probably be assigned to the tractor.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Percentage of Overhead and G&A Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the overhead and G&A costs to the truck and another portion to the trailer. The costs are allocated the same as the labor costs.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

- Percentage of Other Fixed Operating Costs Allocated to Tractor: Because the final costs are split into a tractor and trailer cost, it is necessary to assign a portion of the other fixed operating costs to the truck and another portion to the trailer.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.11.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the tractor and the trailers, respectively, are pooled together so that the hydrogen cost can be determined for each component. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.12 H2 Liquefier

This tab is used to calculate the contribution to the delivered hydrogen cost for a hydrogen liquefier. A liquefier would most likely be located at a central hydrogen production plant to convert the hydrogen to liquid before transportation. However, it is also feasible that a liquefier might be located at a terminal, where gaseous hydrogen delivered by pipeline, for example, would be converted to liquid for final delivery. There are a few hydrogen liquefiers located throughout North America, but the high operating costs and inefficient operation have limited widespread manufacture of the liquefiers.

Figure 17. An Air Products hydrogen liquefaction facility in Sacramento, CA (photo courtesy of Air Products and Chemical's website, at www.airproducts.com).

5.12.1 Design Concept

The liquefier tab is designed to cost a single liquefier unit. The model can size and cost a liquefier based on an idealized liquefier power equation and an energy efficiency based on literature data (this will be described later). As an alternative, the user can opt to enter their own efficiency to cost and size the unit. When using this tab, it is important to note that the energy efficiency of a hydrogen liquefaction unit decreases significantly when the flowrate drops below 5,000 kg/day.

In this tab, the user has the option to enter their own capital costs, or to use the results obtained from a cost curve developed the H2A Delivery Team based on literature data. The use of the cost curve, and the basis for the values, is described in the Capital Cost section.

5.12.2 Key Assumptions

- The inlet and outlet pressures for the liquefier are both assumed to be 1 atm.
- The feed to the system is pure hydrogen.

5.12.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Liquefier Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

5.12.4 Design Inputs

The design inputs table is used for entering values to determine the size of hydrogen liquefier required. This table contains several yes/no toggle switches, which enhance the flexibility of the model. The items included in this table are described below.

- Average Hydrogen Flowrate Out: Enter the average hydrogen flowrate out of the liquefier in kg/day. Please note that this entry is the amount of hydrogen that you actually want to have delivered from the liquefier. The value entered in this cell will be increased in the calculation section if any hydrogen is assumed to be lost during the liquefaction process (hydrogen losses are entered in a later cell).
- Peak Hydrogen Flowrate Out: Enter the peak hydrogen flowrate out of the liquefier in kg/day.
- Capacity Factor: Calculated by dividing the Average Hydrogen Flowrate Out by the Peak Hydrogen Flowrate Out.
- Use Liquefier Electric Efficiency Calculation?: The user should select ***yes*** or ***no*** using the toggle switch.

  If ***yes*** is selected, then the graph shown below, developed using data described by Bossell in "The Future of the Hydrogen Economy: Bleak or Bright" (Bossel, *et al.*, 2003) is used. The graph depicts how the efficiency of a liquefier decreases significantly as the design capacity, or hydrogen flowrate, drops below 5 tonne/day. The graph, as well as cooresponding data, is also shown in the Liquefier Cost_Efficiency tab in the model.

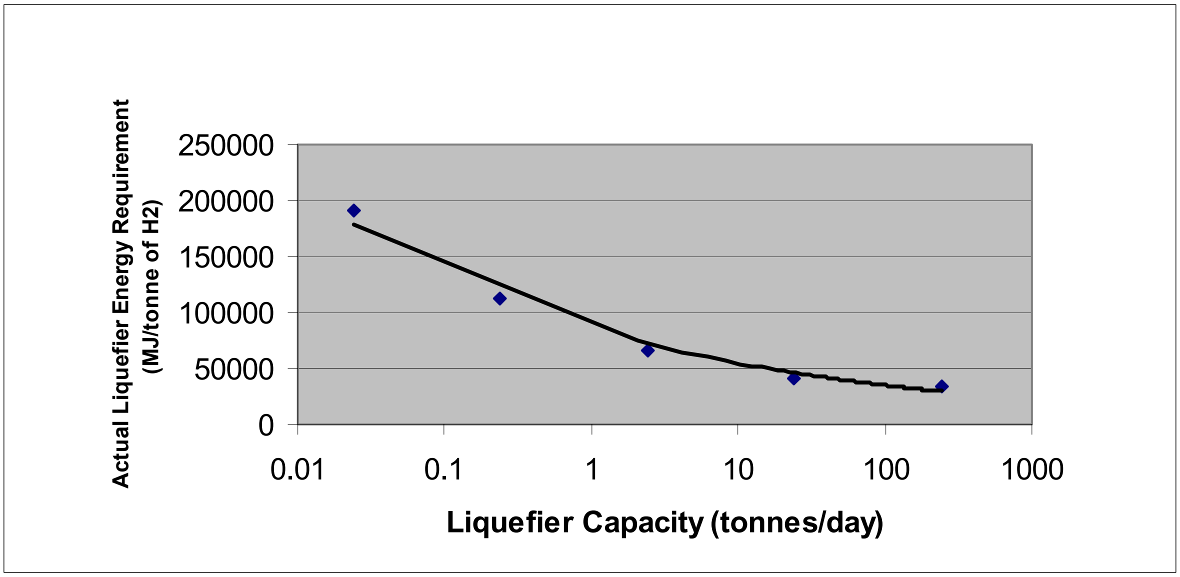

Figure 18. Plot of actual liquefier energy requirement versus liquefier capacity (Bossel, *et al*., 2003).

If the user selects ***no***, then he or she must enter a value for liquefier efficiency in the next cell. The next cell, labeled "Please enter the Liquefier Electrical Efficiency", will only appear if ***no*** is selected.

- Default Hydrogen Inlet Temperature: The value is fixed at 25°C. The temperature entered here is a reference for the default inlet entropy and enthalpy values specified later in this table.

- Use Default Inlet Hydrogen Temperature?: The user should select ***yes*** or ***no*** using the toggle switch.

  If ***yes*** is entered, no further action is necessary, and the cell below will remain blank.

  If ***no*** is entered, the cell immediately below will activate, and tell the user to "Please Enter an Inlet Temperature". The user should note that if ***no*** is selected, inlet enthalpy and entropy values will need to be supplied which correspond to the new Inlet Temperature. The National Institute of Standards and Technology (NIST, http://www.nist.gov) is a good source for hydrogen entropy and enthalpy data.

- Default Hydrogen Outlet Temperature: The value is fixed at 20K. The temperature entered here is a reference for the default outlet entropy and enthalpy values specified later in this table.

- Use Default Outlet Hydrogen Temperature?: The user should select ***yes*** or ***no*** using the toggle switch.

If ***yes*** is entered, no further action is necessary, and the cell below will remain blank.

If ***no*** is entered, the cell immediately below will activate, and tell the user to "Please Enter an Outlet Temperature". The user should note that if ***no*** is selected, outlet enthalpy and entropy values will need to be supplied which correspond to the new Inlet Temperature. NIST (http://www.nist.gov) is a good source to find hydrogen enthalpy and entropy data.

- Default Inlet Hydrogen Entropy: This cell will show a value of 53.382 kJ/kg.K, which corresponds to the hydrogen entropy at the default inlet temperature of 26°C. If the user opted to enter their own inlet temperature, the value in this cell will still appear, but will not be used in any calculations.

- Default Outlet Hydrogen Entropy: This cell will show a value of -0.132 kJ/kg.K, which corresponds to the hydrogen entropy at the default inlet temperature of 20K. If the user opted to enter their own outlet temperature, the value in this cell will still appear, but will not be used in any calculations.

- Default Inlet Hydrogen Enthalpy: This cell will show a value of 3,929.6 kJ/kg, which corresponds to the hydrogen enthalpy at the default inlet temperature of 26°C. If the user opted to enter their own inlet temperature, the value in this cell will still appear, but will not be used in any calculations.

- Default Outlet Hydrogen Enthalpy: This cell will show a value of -2.7 kJ/kg, which corresponds to the hydrogen enthalpy at the default inlet temperature of 20K. If the user opted to enter their own outlet temperature, the value in this cell will still appear, but will not be used in any calculations.

If the user choses to use the specified default inlet and outlet temperatures, then no more entry is required in the Design Inputs table, and the next four rows will remain blank.

However, if the user opted to enter their own inlet or outlet temperature, then a combination (if one default temperature was used) or all (if neither default temperature was used) of the next four rows will require input. The values that the user will need to enter are the hydrogen entropy/enthalpy at the new inlet and/or outlet temperature.

5.12.5 Scenario Inputs

- Hydrogen Loss During Liquefaction: Enter, as a percentage of the feed flowrate, the amount of hydrogen that is lost during the liquefaction process.

5.12.6 Calculations

The derivation for the calculations shown in this section is based on data presented by Barron (1985).

The thermodynamically ideal system for hydrogen liquefaction assumes reversible isothermal compression and a reversible isentropic expansion. The First Law of Thermodynamics for steady flow of the thermodynamically ideal system can be written as follows:

$$\dot{Q}_{net} - \dot{W}_{net} = \sum_{outlets} \dot{m}(h + \frac{v^2}{2g_c} + \frac{gz}{g_c}) - \sum_{inlets} \dot{m}(h + \frac{v^2}{2g_c} + \frac{gz}{g_c})$$

We assume that the kinetic and potential energy terms in this equation are small compared to the enthalpy terms, so the equation can be rewritten as follows:

$$\dot{Q}_{net} - \dot{W}_{net} = \sum_{outlets} \dot{m}h - \sum_{inlets} \dot{m}h$$

Where:
$\dot{Q}_{net}$ = net heat
$\dot{W}_{net}$ = the idealized net work required by the liquefier
$\dot{m}$ = the design capacity of the liquefier
h = enthalpy.

With the simple system described above, this equation can be written as follows:

$$\dot{Q}_{net} - \dot{W}_{net} = \dot{m}(h_{in} - h_{out})$$

The Second Law of Thermodynamics for a reversible and isothermal process Carnot process (such as the process described here) can be written as follows:

$$\dot{Q}_{net} = \dot{m}T_1(s_{in} - s_{out})$$

Combining the previous two equations provides the following expression that is used to determine the work requirement for the ideal system:

$$-\frac{\dot{W}_{net}}{\dot{m}} = T_{1(}(s_{in} - s_{out}) - (h_{in} - h_{out})$$

Where all variables have been defined previously except::

T_1 = the inlet temperature to the liquefier (specified in the Design Inputs Table)
s_{in} = the hydrogen entropy at the inlet temperature (specified in the Design Inputs Table)
s_{out} = the hydrogen entropy at the outlet temperature (specified in the Design Inputs Table)
h_{in} = the hydrogen enthalpy at the inlet temperature (specified in the Design Inputs Table)
h_{out} = the hydrogen enthalpy at the outlet temperature (specified in the Design Inputs table).

The theoretical power required for liquefaction is calculated using this formula.

- Net Hydrogen Delivered Per Year: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 days/year.

- Theoretical Power Requirement: This value is calculated according to the following formula (derivation described previously in this section).

$$-\frac{\dot{W}_{net}}{\dot{m}} = T_{1(}(s_{in} - s_{out}) - (h_{in} - h_{out})$$

- Actual Power Requirement: The value calculated in this cell relates back to the Design Inputs table where the user was asked whether they wanted to use the H2A Energy Efficiency calculation.

  If ***yes*** was selected, then the actual power requirement is calculated using the curve fit from the graph shown in Figure 18. The formula is:

  $$P_{liq} = P_{req} \frac{F_{avg}}{1 - loss}$$

  Where:

  $P_{req} = 85959(\frac{F_{avg}}{1 - loss})^{-0.1951}$ which is the curve fit from Figure 18.
  F_{avg} = average hydrogen flowrate out (from Design Inputs table)
  loss = hydrogen loss during liquefaction (from Design Inputs table).

  If ***no*** was selected, then the actual power requirement is calculated using the following equation:

  $$P_{liq} = \frac{\dot{W}_{net}}{\eta_{liq}}$$

  Where:

  $\dot{W}_{net}$ = the idealized net work required by the liquefier

  η_{liq} = the liquefier electrical efficiency (as specified in the Design Inputs table)

- Liquefier Electrical Efficiency: The Theoretical Power Requirement is divided by the Actual Power Requirement to determine this value.

5.12.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.12.8 Capital Investment

This table is where the capital costs for the liquefier are entered.

The H2A Delivery team has developed a cost curve that can estimate the capital cost of a liquefier. The data for the cost curve was taken from several literature sources (Directed Technologies, Inc., *et al*., 1997; Simbeck, *et al.*, 2002; Taylor, *et al.*, 1986). As opposed to the cost curve in the compressor tab, the liquefier costs are only for the purchase of the unit. Other direct and indirect capital costs (such as installation, contingencies, property taxes and engineering) need to be entered so that the Total Capital Investment can be determined.

The cost data for the liquefier came from journal articles and reports that were published from 1986 – 2002. Therefore, the costs were inflated to year 2005 dollars using the GDP Implicit Deflator Price Index which is found in the Energy Information Administration's Short Term Energy Outlook. A plot showing the cost, in 2005 dollars, of a liquefier as a function of design capacity is shown in Figure 19.

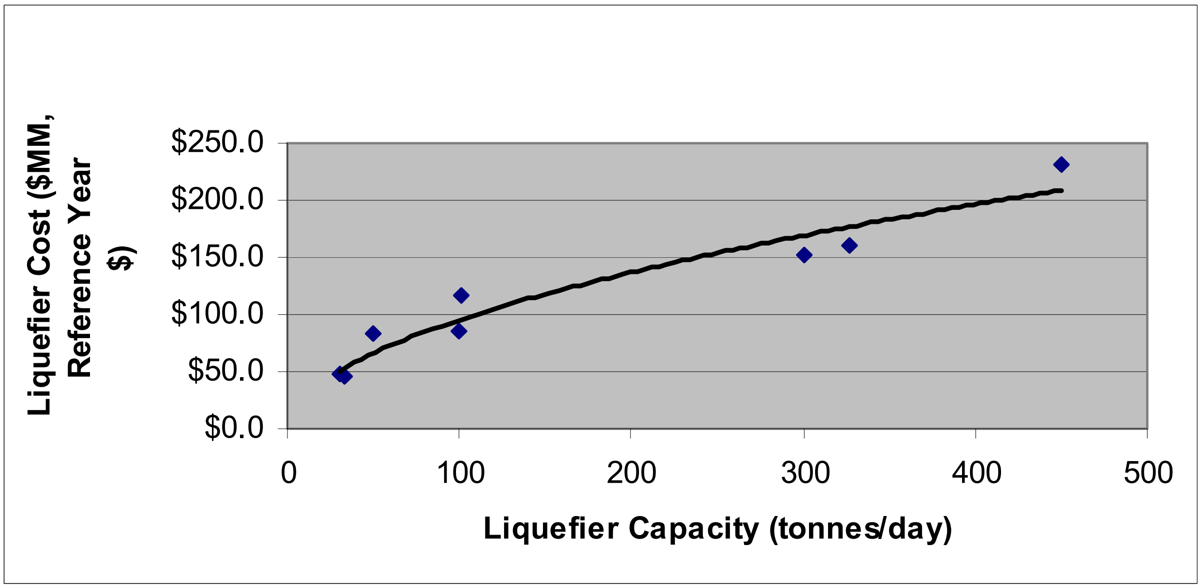

Figure 19. A plot showing the compressor cost as a function of compressor power draw (Directed Technologies, Inc., *et al.*, 1997; Simbeck, *et al.*, 2002; Taylor, *et al.*, 1986).

The data used to construct the plot shown in Figure 19, as well as a copy of the plot, are included on the Liquefier Cost_Efficiency tab in the model.

The specific entries for this table are described below.

- Use the H2A Liquefier Costs…: The entry for this cell uses a yes/no toggle switch. If ***yes*** is selected, then:
    - The H2A liquefier cost function, described above, is used for the liquefier capital cost. No other entry is required in the Capital Cost table.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Liquefier Package: The calculation in the "Value" column reads the design capacity of the liquefier as entered in the Design Inputs tab. The specific entries required in this row depend on whether the user opted to use the H2A liquefier costs. If ***yes*** was selected, then the value in the "Installed Costs from H2A Data" is filled based on the curve fit to the graph shown in Figure 19.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Balance of Component: This item includes any other equipment that might be required for operation of a liquefier that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment. The following items are either calculated, or require entry in this table.

- Land Required: The H2A Delivery team has assumed that a 30 tonne/day liquefier will require approximately 25,000 m^2 of land. The land required is therefore calculated by taking the ratio of the design capacity entered in the Design Inputs tab to 30 tonne/day, and then raising the result to the 0.6 power. The result of the calculation is multiplied by 25,000 to give the amount of land required.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Installed Capital Cost: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.12.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the liquefier are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: The user should enter the total labor-hours per year required to operate the liquefier. In entering this value, the user should be aware the a liquefier unit is similar to a small plant in that there will probably need to be operators onsite at all times.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.

- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

The annual energy requirement is calculated using the following formula.

$$E_{ann} = 8760 P_{liq}$$

Where:

P_{liq} = actual average power requirement (calculated in the Calculations table).

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total utility cost is determined by multiplying either the user-input fuel cost or the H2A value by the Annual Energy Requirement.

If ***no*** is selected, the Electricity Cost ($/kWh) disappears, and a new cell requesting the user to input an electricity cost, in $/kWh, appears. This value is then multiplied by the electricity consumption to determine an annual electricity cost.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.
- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.
- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.
- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.
- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.
- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.
- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.
- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.
- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.
- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.
- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.12.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the liquefier are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.13 Bulk Liquid Hydrogen Storage

This tab is used to calculate the contribution to the delivered hydrogen cost for bulk liquid hydrogen storage. The scale of storage that this tab is designed to handle is on the terminal level. For example, at a liquefaction plant, there will need to be enough storage so that if the liquefier goes offline, the facility will still be able to provide hydrogen to customers.

Figure 20. A picture of a liquid hydrogen tank, along with several liquid hydrogen delivery trucks (Photo obtained from NASA's website at www.nasa.gov).

5.13.1 Design Concept

This tab is used for designing and costing a bulk liquid hydrogen storage system. Current technology typically involves spherical storage tanks. An example of a liquid hydrogen storage tank is shown in Figure 20.

In a typical liquid hydrogen storage operation, the tanks are not allowed to completely empty. The primary reason for not emptying tanks completely is to keep the internal parts cold, which minimized boil-off. This tab is designed using this philosophy. The user can enter the percentage of the total storage capacity that is available. The calculations will then determine the actual amount of liquid hydrogen stored.

5.13.2 Key Assumptions

- No energy is required to operate the bulk hydrogen storage system. A liquefier to transform gaseous hydrogen to liquid hydrogen can be analyzed using the Liquefier tab in the model.

- The storage system is assumed to be filled and emptied continuously during the year. Thus, the amount of liquid hydrogen delivered from this component is calculated by multiplying the Average Demand from the storage system by 365 days/year.

5.13.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Bulk Liquid Hydrogen Storage Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

5.13.4 Design Inputs

The design inputs table is used for entering values to determine how much hydrogen will be stored in the bulk liquid hydrogen storage system. This table contains a yes/no toggle switches to enhance the flexibility of the model. The user has the option to size the storage system based on an Average Demand on the storage system and the number of days of storage. As an alternative, the user can simply enter the size of a storage system where the capacity is known.

If ***yes*** is selected by the user for the question "Size Liquid Hydrogen Storage Based on Storage Time and Average Hydrogen Demand?", then the following inputs are required.

- Average Hydrogen Demand: Enter the average amount of hydrogen that the system that the storage system is serving need to be provide.

If ***no*** is selected for the question "Size Liquid Hydrogen Storage Based on Storage Time and Average Hydrogen Demand?", then input is required only in the following cell.

- Desired Storage Capacity: The user should enter the capacity, in kg, of the liquid hydrogen storage system that they would like to analyze.

The remaining two cells in the Design Inputs tab require inputs regardless of whether ***yes*** or ***no*** was selected.

- Useable Percent of Liquid Storage Unit (%): The user needs to enter a percentage of total liquid hydrogen storage capacity that is useable. A certain percentage of the liquid hydrogen stored should remain in the storage vessel to keep the internal parts cold, therefore eliminating boil-off concerns during charging.

- Boil-off Rate: During storage, a portion of the liquid hydrogen will boil-off and be vented through a relief value on the vessel. This value should be entered as a percentage loss per day, based on the total volume of the storage system.

5.13.5 Scenario Inputs

- Number of Days of Storage: If the user answered ***yes*** to the question "Size Liquid Hydrogen Storage Based on Storage Time and Average Hydrogen Demand?", then the user needs to enter the number of days of storage desired. This input is multiplied by the average hydrogen demand to determine the size of the desired liquid hydrogen storage system.

5.13.6 Calculations

- Days of Storage: Number of Days of Storage, from the Scenario Inputs table, is fed to this cell.

- Design Storage Capacity: The value calculated in this cell depends on how the user answered the question "Size Liquid Hydrogen Storage Based on Storage Time and Average Hydrogen Demand?".

  If the user entered ***yes***, this value is calculated using the following equation.

  $$C_{des} = \frac{T_{store} F_{avg}}{A_{\tan k}(1 - Loss)}$$

  Where:

  T_{store} = number of days of storage (from the Scenario Inputs table)
  F_{avg} = average hydrogen demand (from the Design Inputs table)
  A_{tank} = useable percent of liquid storage unit (from the Design Inputs table)
  $Loss$ = boil-off losses (from the Design Inputs table)

  If the user entered ***no***, the Desired Storage Capacity, entered in the Design Inputs Table, is used as the numerator in the above equation, rather than $T_{store}F_{avg}$.

- Useable Storage Capacity: This value is calculated using the following formula.

  $$C_{use} = C_{des} A_{\tan k}(1 - loss)$$

  Where all the variables have been defined previously.

- Storage System Water Volume: This value is calculated by dividing the Design Storage Capacity by the density of liquid hydrogen. The density for liquid hydrogen is pulled from the Physical Property tab.

- Net Hydrogen Delivered: This value is calculated by multiplying the Average Hydrogen Demand by 365 (days/yr).

5.13.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.13.8 Capital Investment

This table is where the capital costs for the bulk liquid hydrogen storage system are entered.

The H2A Delivery team has developed a cost curve that can estimate the capital cost of a bulk liquid hydrogen storage system. The data for the cost curve was taken several literature sources

(Directed Technologies, Inc., *et al.*, 1997; Taylor, *et al.*, 1986). As opposed to the cost curve in the compressor tab, the liquid hydrogen storage costs are only for the purchase of the unit. Other direct and indirect capital costs (such as installation, contingencies, property taxes and engineering) need to be entered so that the Total Capital Investment can be determined.

The cost data for the liquefier came from journal articles and reports that were published from 1986 and 1997. Therefore, the costs were inflated to year 2005 dollars using the GDP Implicit Deflator Price Index which is found in the Energy Information Administration's Short Term Energy Outlook. A plot showing the cost, in 2005 dollars, of a liquid hydrogen storage system as a function of design capacity is shown in Figure 22.

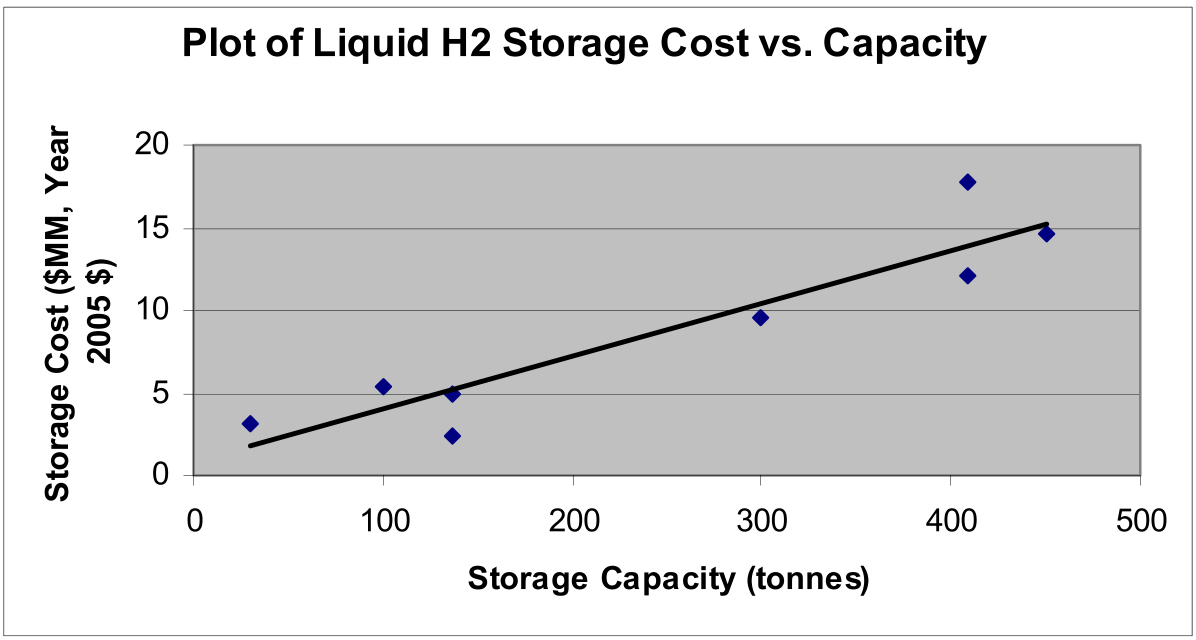

Table 21. Plot of liquid hydrogen storage cost vs. design capacity (Directed Technologies, Inc., *et al.*, 1997; Taylor, *et al.*, 1986).

The data used to construct the plot shown in Figure 21, as well as a copy of the plot, are included on the Liquid Storage Costs tab in the model.

The specific entries for this table are described below.

- <u>Use the H2A Liquid Storage Costs…:</u> The entry for this cell uses a yes/no toggle switch. If ***yes*** is selected, then:
    - The H2A liquid storage cost curve, described above, is used for the capital cost. Not other entry is required in the Capital Cost table.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- <u>Liquefier Storage:</u> The calculation in the "Liquid Storage Capacity" column reads the design capacity of the liquid storage system as calculated in the Calculations table. The specific entries required in this row depend on whether the user opted to use the H2A liquefier costs. If ***yes*** was selected, then the value in the "Installed Costs from H2A Data" is filled based on the curve fit to the graph shown in Figure 22.

If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Balance of Component: This item includes any other equipment that might be required for operation of a liquid storage system that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment. The following items are either calculated, or require entry in this table.

- Land Requirement: The land requirement is calculated based on the assumption that the liquid storage tank will be spherical. The land required is then assumed to be 200% of the footprint required by the spherical tank. The equation used to calculate the land area is shown below.

$$Land = 2\pi\left(\frac{0.75V_{\tan k}}{\pi}\right)^{2/3}$$

Where

V_{tank} = the volume of the storage tank (from the Calculations table).

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of the liquid hydrogen storage tank.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Installed Capital Cost: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.13.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the liquid hydrogen storage tank are entered. The table is divided into two sections: labor, and the remainder of costs. The liquid hydrogen tank does not require any energy for operation, and thus the user does not need to enter any fuel/utility information. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: The user should enter the total labor-hours per year required to operate the liquid hydrogen storage tank.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.

- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.

- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the liquid hydrogen storage tank.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom of the table.

5.13.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor and other O&M costs for the liquid hydrogen storage tank are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.14 H2 Compressor

This tab is used to calculate the contribution to the delivered hydrogen cost for hydrogen compression. For example, a compressor will be required to raise the pressure of the hydrogen produced at a central facility to the pressure in a pipeline. These compressors are also integral parts of the pipeline delivery network and a compressed gas terminal. At a terminal, compressors are required to fill the compressed gas trucks and to fill the high pressure storage tanks. At a geologic storage site, a compressor is required both to charge and discharge the cavern. The user will realize that the calculations explained in this section are integral to the operation of several other tabs in the Components Model.

Figure 22. A hydrogen compressor that can be used to boost the pressure from the production plant to a specified pipeline pressure.

5.14.1 Design Concept

The compressor tab is designed to cost a centralized or large-scale compressor that can raise the pressure of a defined hydrogen flowrate from one pressure to another. A separate tab is used to calculate the cost of a forecourt compressor. The model includes an idealized compressor power calculation (defined in the introduction), or the user can opt to cost the compressor based an input of kW/kg of hydrogen/hour.

In many hydrogen compression applications, the compressor units are spared to ensure a high level of operational availability. Sparing is extremely important when considering reciprocating compressors. To this end, the tab allows the user to enter the number of purchased compressors along with the number of compressors operating at any one time.

In this tab, the user has the option to enter their own capital costs, or to use the results obtained from a cost curve developed the H2A Delivery Team based on data in the Oil and Gas Journal for natural gas compressors. The use of the cost curve, and the basis for the values, is described in the Capital Cost section.

5.14.2 Key Assumptions

- The user needs to know either the number of stages in the compressor or the compression ratio per stage. In selecting these values, the user must ensure that typical material temperature constraints are not exceeded, as the model does not check interstage or exit temperatures.

- The theoretical power requirement calculation assumes that the compression work is equally divided between the stages and that an intercooler between each stage brings the gas temperature back to the original inlet temperature.

- It is assumed that there are not pressure drops in the after-cooler or interstage coolers.

- An electrical-powered compressor is assumed. The tab does not allow for the calculation of costs associated with compressors fed with other fuels such as natural gas or hydrogen.

5.14.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Hydrogen Compressor Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

2. No capital costs are entered.

5.14.4 Design Inputs

The design inputs table is used for entering values that determine the size of compressor required. This table contains a number of yes/no toggle switches, which enhance the flexibility of the model. The items included in this table are described below.

- Average Hydrogen Flowrate Out: Enter the average hydrogen flowrate out of the compressor in kg/day. Please note that this entry is the amount of hydrogen that you actually want to have delivered from the compressor. The value entered in this cell will be increased in the calculation section if any hydrogen is assumed to be lost during the compression process (hydrogen losses are entered in a later cell).

- Peak Hydrogen Flowrate Out: Enter the peak hydrogen flowrate out of the compressor in kg/day.

- Inlet Pressure: The user should enter the suction pressure to the compressor in this cell. It is important to note that no vacuum pressures can be entered.

- Outlet Pressure: The user should enter the compressor outlet pressure in this cell. It is important to note that no vacuum pressures can be entered.

- Inlet Hydrogen Temperature: Enter the temperature of the hydrogen gas entering the suction end of the compressor.

- C_p/C_v Ratio: Enter the ratio of the constant pressure specific heat for hydrogen and the constant volume specific for hydrogen. H2A uses a value of 1.4 for this ratio.

- Enter the Number of Installed Compressors: As mentioned earlier in this section, to ensure high compressor availability, compressors may need to be spared. Enter the number of compressors that will be purchased in this cell.

- Enter the Number of Compressors in Operation at Any Time: Enter the number of compressors that will be processing hydrogen. For example, a user may enter 3 as the number of compressors required, but only have 2 operating at any one time. In that instance, one compressor is a spare.

The next cell, labeled "Design Compressor based on a Compression Ratio per Stage?", contains a yes/no toggle switch. A compression ratio per stage is defined as the outlet pressure from the stage divided by the inlet pressure to that stage. If ***yes*** is selected, the user must enter a value in the following cell:

- Enter Compression Ratio per Stage: The design compression ratio per stage needs to be entered in this cell. The model will use this value to calculate the number of stages required for the compressor.

If ***no*** is selected, the user must enter a value in the following cell:

- Enter the Number of Stages: The number of stages in the compressor should be entered. The model will calculate the pressure ratio.

The next important consideration for the user is the isentropic compressor efficiency. The cell, labeled "Isentropic Compressor Efficiency Available?", includes a yes/no toggle switch. The isentropic efficiency is determined by assuming that the compressor process occurs without an increase in entropy. If ***yes*** is selected with the toggle switch, the user must enter a value in the following cell:

- Isentropic Compressor Efficiency: Please enter the isentropic compressor efficiency in this cell. This value is used to calculate the actual power consumed by the compressor.

If ***no*** is selected, the user must enter values in the following cells:

- Type of Efficiency Available: Since the isentropic efficiency of the compressor is not available, the user needs to specify the type of compressor efficiency that is available.

- Compressor Efficiency: The user should enter the compressor efficiency as described in the previous cell. Since the isentropic efficiency is not available, the model will use this efficiency to calculate the actual power consumed by the compressor.

As mentioned previously, the user can opt to use the idealized compressor power equation described previously, or simply enter the kW/kg of hydrogen/hour required for compressor. Therefore, the next cell, labeled "Use Isentropic Efficiency to Calculate the Power Requirement", is a yes/no toggle switch. If ***no*** is selected, then a value needs to be entered into the following cell:

- Compressor Power Requirement: Please enter the power draw for the compressor, in kW/kg of hydrogen/hour, for the compressor under investigation.

If ***yes*** is selected, no further input is required.

- Hydrogen Lost During Compressor: Please enter the amount of hydrogen that is lost during the compression process as a percentage of the feed flowrate.

- Type of Compressor: Please use the pull-down menu to select the type of compressor described by the input data. This is an optional entry, but is useful for other users to understand what type of compressor was envisioned.

5.14.5 Calculations

Please see the Compressor Power Calculations section in the General Comments section of this manual for a detailed description of how the idealized power equation is defined.

- Gas Contant: The standard value of 8.3144 kJ/K.kg_mol is used in the H2A Delivery case.

- Mean Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual.

- Pressure Ratio: If a pressure ratio was entered in the Design Inputs table, then that value is simply fed to this cell. However, if the number of stages was entered, then the following formula is used to calculate the pressure ratio.

$$P_R = 10^{\frac{\log(P_{out}) - \log(P_{in})}{N_s}}$$

Where:

P_{out} = pressure out of compressor (from Design Inputs table)
P_{in} = inlet pressure to compressor (from Design Inputs table)
N_s = number of stages (from Design Inputs Table)

- Number of Stages: If the number of stages was entered in the Design Inputs table, then that value is simply fed to this cell. However, if the pressure ratio per stage was entered, then the following formula, rounded up to the nearest integer, is used to calculate the number of stages.

$$N_s = \frac{\log(P_{in}) - \log(P_{out})}{\log(P_R)}$$

Where the variables are defined as in the pressure ratio equation.

- Net Hydrogen Delivered Per Year: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 days/year.

- Design Flowrate to Each Compressor: This value is determined using the following equation:

$$F_{des} = \frac{F_{peak}}{N_c / 1 - loss}$$

Where:

F_{peak} = Peak hydrogen flowrate out (from Design Inputs table)
N_c = Number of compressors in operation at any time (from Design Inputs table)
$loss$ = hydrogen losses (from Design Inputs table)

- Theoretical Power Requirement: The equation used in this cell was described in the General Comments section of this manual. The design flowrate to each compressor is used in this equation. N/A will show up in this cell if the user opted to enter a power requirement.

5.14.6 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.14.7 Capital Investment

This table is where the capital costs for the compressor are entered.

The H2A Delivery team has developed a cost curve that can estimate the capital cost of a compressor. The data for the cost curve was taken from a 2000 article in the Oil and Gas Journal (True, 2000). The costs included in that article represented not only the purchase costs for natural gas compressors, but also the cost of an aftercooler and the costs of other direct and indirect capital costs (such as installation, contingencies, property taxes and engineering).

We have adapted the data to approximate the capital cost of a hydrogen compressor. The cost data from the Oil and Gas Journal were inflated to year 2005 dollars using the GDP Implicit Deflator Price Index which is found in the Energy Information Administration's Short Term Energy Outlook. A plot showing the cost, in 2005 dollars, of a compressor as a function of power draw is shown in Figure 23.

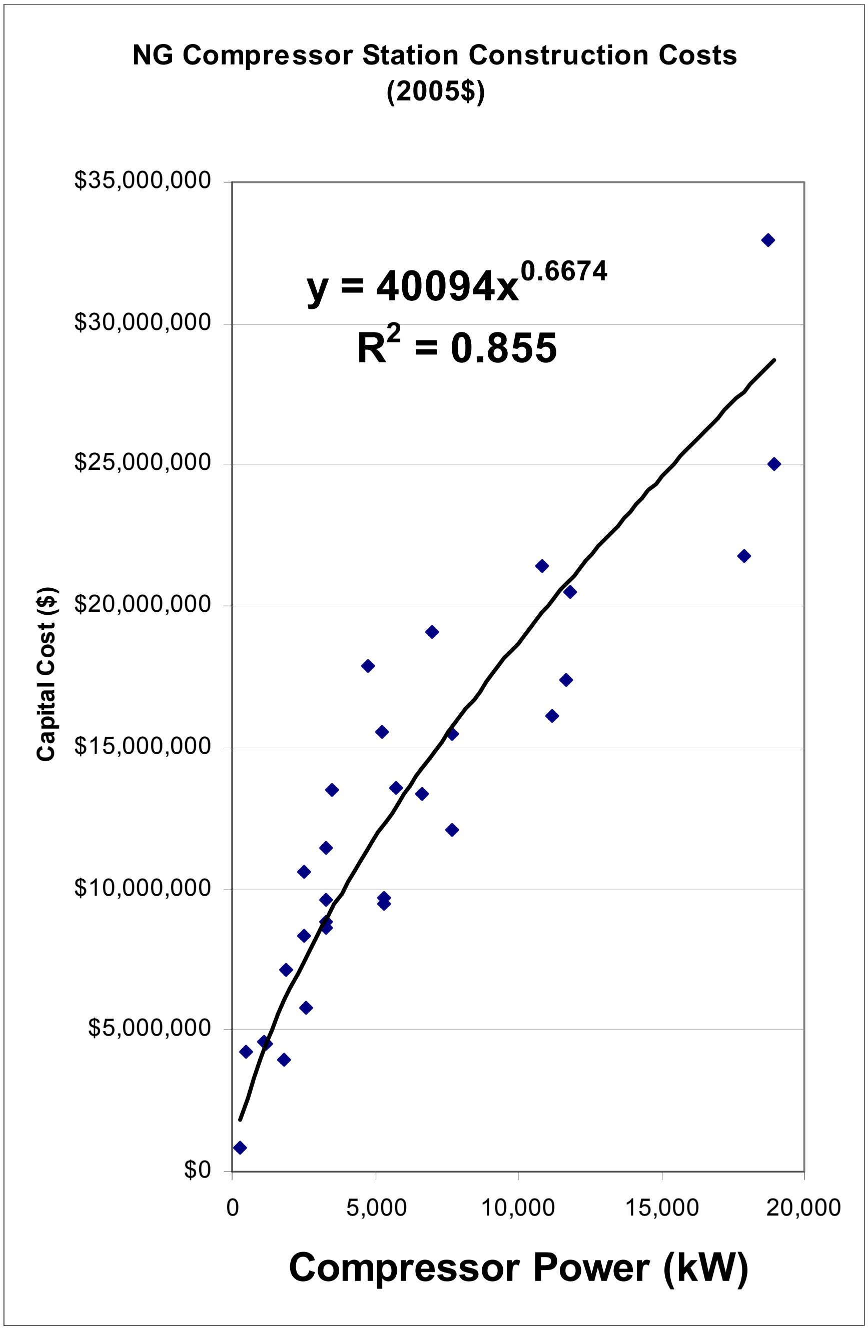

Figure 23. A plot showing the compressor cost as a function of compressor power draw (True, 2000).

Besides adjusting the compressor capital costs for inflation, the capital cost determined from the data shown in the graph is multiplied by 1.3. The H2A Delivery Team believes that the capital cost of a hydrogen compressor will be higher than that for a natural gas compressor. There are several reasons why this factor was chosen and they are each based on the differences between a hydrogen compressor and a natural gas compressor.

One of the differences is the type of compressor used for the application. Centrifugal compressors are typically used in large natural gas compression applications. Because hydrogen has a very low molecular weight, centrifugal compressors can not currently be used for hydrogen compression. For current large compressor applications, most hydrogen compressors are of the reciprocating type.

Another difference will be the materials of construction. It is a fair assumption that more robust materials will need to be used for the casing, piston housings and seals. The H2A Delivery team felt that multiplying the compressor cost from the Oil and Gas Journal by 1.3 would adequately, albeit conservatively, account for the differences in hydrogen and natural gas compression.

The specific entries for this table are described below.

- Use the H2A Compressor Costs…: The entry for this cell uses a yes/no toggle switch. If ***yes*** is selected, then:

    - The H2A compressor cost function, described above, is used for the compressor capital cost. Not other entry is required in the Capital Cost table.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Number of Compressor Units: This value is linked to the number of compressors required, which was specified in the Design Inputs table.

- Power Required per Compressor (kW): The calculation in the "Value" column of this cell depends on whether the user opted to used the idealized power equation or to simply enter a power requirement (kW/kg of H2/hr). If the idealized power equation is used, then the following equation applies.

$$P_{comp} = \frac{P_{ideal}}{\eta_{isentrop}}$$

  Where:

  P_{ideal} = theoretical power requirement (calculated in the Calculations table)
  $\eta_{isentrop}$ = isentropic compressor efficiency (from Design Inputs table).

  If a power requirement was entered in the Design Inputs table, then the following equation is used.

$$P_{comp} = P_{req} \frac{F_{peak}}{24}$$

  Where:

  P_{req} = power requirement per kg/hr of hydrogen (from Design Inputs table)
  F_{peak} = peak hydrogen flowrate out (from Design Inputs table).

If the user opted to use the H2A Compressor costs, then the entry under "Installed Costs from H2A Data" column will contain a number. Otherwise, this entry will contain "N/A", and the user will need to either enter a value in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

- Balance of Component: This item includes any other equipment that might be required for operation of a compressor that has not already been included in the previous items.

It is important to note that the capital cost entered for the compressor is on a per unit basis. The Balance of Component, on the other hand, should be entered on a net basis.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment.

If ***yes*** was entered for using the H2A Compressor Capital Costs, no entry is required in this table. The data from the Oil and Gas Journal used for the H2A capital cost curve included all the items included in this table.

If the user opted not to use the H2A Compressor Capital Costs, then the following inputs are required.

- Land Required: Please enter the amount of land required for the compressor. This value should include any necessary safety offsets required around the compressor.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site (such as grating and pouring a cement base) should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of these compressors.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Installed Capital Cost: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.14.8 Operating and Maintenance Costs

In this table, the annual costs required for operating the compressor are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: The user should enter the total labor-hours per year required to operate the compressor.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.

- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

The annual energy requirement for the compressor is different from the value specified in the Capital Cost table. The capital cost of the compressor needs to be based on a unit that is capacle of processing the peak hydrogen flowrate. However, during a typical operating year, the feed flowrate will fluctuate. Therefore, the average hydrogen flowrate out is used as a basis to calculate the annual energy requirement (see the beginning of this manual for a discussion of peak and average flowrates).

If the user opted to use the idealized power equation, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 \frac{F_{avg}}{\eta_{isentrop}} ZRT_1 N_{st} \left(\frac{k}{k-1} \right) \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{kN_{st}}} - 1 \right]$$

Where:

$\eta_{isentrop}$ = isentropic compressor efficiency (from Design Inputs table)
F_{avg} = average hydrogen flowrate out, converted to mol/sec (from Design Inputs table)
R = gas constant (specified in the Calculation table)
T_1 = inlet gas temperature, converted to K (from Design Inputs table)
N_{st} = number of compression stages (calculated in the Calculations table)
k = ratio of specific heats (specified as Cp/Cv in the Design Inputs table)
p_2 = outlet pressure (specified in the Design Inputs table)
p_1 = inlet pressure (specified in the Design Inputs table).

If the user opted to input a compressor power requirement per kg/hr of hydrogen, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 P_{req} \frac{F_{avg}}{24}$$

P_{req} = Power requirement per kg/hr of hydrogen (from Design Inputs table)
F_{avg} = average hydrogen flowrate out (from Design Inputs table).

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total utility cost is determined by multiplying either the user-input fuel cost or the H2A value by the Annual Energy Requirement.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.
- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.
- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.
- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.14.9 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the compressors are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

5.15 H2 Pipeline

This tab is used to calculate the contribution to the delivered hydrogen cost for hydrogen pipelines. The tab can either calculate the cost of a specific length of pipeline, or for a network of pipelines. It is important to note that the pipeline tab will not design a pipeline system for the user. Rather, the tab is designed to take lengths of pipeline that a user may have developed during a planning effort, and determine a cost based upon those lengths. In a possible future hydrogen infrastructure, pipelines have been envisioned to move hydrogen from central plants to a city gate (transmission pipelines), from city gates to service lines (trunk pipelines) and from trunk pipelines to end use point (distribution or service pipelines). A similar infrastructure design is used to move natural gas around the country.

Figure 24. What a hydrogen pipeline might look like coming into a terminal or other gathering station (Photo downloaded from Praxair 2003 Annual Report, available at www.praxair.com)

5.15.1 Design Concept

The pipeline tab is designed to determine a hydrogen cost contribution for either a single length of pipeline, or a system of transmission, trunk and distribution pipelines. The tab will not design a pipeline system, but will determine the cost of a potential system that the user developed. There are two important considerations on the Pipeline tab that the user needs to recognize:

1. The tab is not based on metric units, as are the other tab. The Panhandle B equation, which is an integral part of this tab, is based on standard units used in the natural gas industry (i.e. psia, scf and °R).

2. The pipeline diameter is constant throughout the entirety of each type. For example, the trunk pipeline sections cannot have more than one diameter.

The model contains a correlation for determining the proper pipeline diameter. If the user wants to specify a pipeline diameter, he or she can use a yes/no toggle to disable the correlation. Otherwise, the user can enter a flowrate, a pipeline length and a desired inlet and outlet pressure, and let the model correlation determine the required diameter. The correlation will also be activated, but in a different form, if the user chooses to enter a pipeline diameter. In this case, the correlation will be used to determine whether the desired outlet pressure is higher than what the actual pressure out of the pipeline would be. It is important to note that the model does not have a specific set of pipeline diameters to utilize. Instead, it will calculate an exact pipeline diameter, and use this value in the calculations (i.e. the final pipeline diameter might be 4.3 inches, even though this is not a standard pipeline size).

In this tab, the user has the option to enter their own capital costs, or to use the results obtained from a cost curve developed by the H2A Delivery Team based on data from a study at the University of California at Davis (UCD). Each year, the Oil and Gas Journal (OGJ) publishes a version of their magazine that shows the costs associated with the installation of natural gas pipelines. A researcher at UCD took data from 13 years (1991 -2003) of OGJ data, and prepared graphs for the following correlations (Parker, 2005). These graphs and correlations can be found on the "Pipeline Costs" Tab at the end of the spreadsheet.

1) Pipeline material cost vs. pipeline diameter: The data in this plot includes the costs for the pipeline materials.

2) Labor cost vs. pipeline diameter: The costs associated with this correlation include those for the labor necessary to install the pipeline.

3) Miscellaneous cost vs. pipeline diameter: The miscellaneous costs include the following: surveys, engineering, supervision, interest, administration and overheads, contingencies, allowances for funds used during construction and FERC fees.

4) Right of way cost vs. pipeline diameter: The right away costs are those associated with the land costs for installing pipeline. It is important to note that these can vary significantly depending on the location of the pipeline (i.e. rural or urban).

5.15.2 Key Assumptions

- No compressor is included in the tab. The user can calculate the cost of the compressor necessary for the pipeline system by using the H2 Compressor tab.

- No energy is required by the pipeline. The energy use for the compressor required can be determined using the H2 Compressor tab.

5.15.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the H2 Pipeline Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

2. No capital costs are entered.

3. The calculated outlet pressure from a specific section of pipeline (i.e. transmission, trunk, or distribution) is less that the desired outlet pressure. This error message will only be activated if the user has opted to insert their own pipeline diameters.

5.15.4 Design Inputs

The design inputs table is used for entering values to determine the size of the hydrogen pipeline system. This table contains several yes/no toggle switches, which enhance the flexibility of the model. The items included in this table are described below.

- Average Hydrogen Flowrate Out: Enter the average hydrogen flowrate out of the hydrogen pipeline in kg/day. Please note that this entry is the amount of hydrogen that you actually want to have delivered from the pipeline. The value entered in this cell will be divided by 1-losses for calculating the required pipeline diameter or for calculating the outlet pressure (depending on whether user enters ***yes*** or ***no*** to using the correlation for determining the pipeline diameter).

- Peak Hydrogen Flowrate Out: Enter the peak hydrogen flowrate out of the pipeline in kg/day.

- Capacity Factor: Calculated by dividing the Average Hydrogen Flowrate Out by the Peak Hydrogen Flowrate Out.

- Use H2A Calculations, using the Panhandle B pipeline equation, to calculate pipeline diameter?: The user should select ***yes*** or ***no*** using the toggle switch.

  If ***yes*** is selected, the Panhandle B Pipeline equation is used to determine the pipeline diameter. The Panhandle B Pipeline equation, shown below, was developed to simulate compressible flow in pipelines (LMNO Engineering, 2003). The equation below allows a user to calculate the appropriate pipeline diameter for a given flowrate, desired pressure drop, pipeline length, as well as other important parameters.

$$q_{sc} = 737\left(\frac{T_{sc}}{P_{sc}}\right)^{1.02}\left(\frac{(P_1^2 - P_2^2)d^{4.961}}{\gamma^{0.961}LT_mZ_m}\right)^{0.51} E$$

Where:

q_{sc} = gas rate at standard conditions (scf/day)
T_{sc} = temperature at standard conditions (°R)
P_{sc} = pressure at standard conditions (psia)
P_1 = inlet pressure (psia)
P_2 = outlet pressure (psia)
d = inside pipeline diameter (in)
γ = mean gas relative density (air = 1)
L = pipeline length (mi)
T_m = mean temperature of pipeline (°R)
Z_m = mean compressibility factor
E = pipeline efficiency

For the pipeline tab, this equation is rearranged so that the pipeline diameter or exit pressure can be calculated. When ***yes*** is selected to the question, the equation used to calculate the required diameter is shown below. In the equation, the following assumptions are made for some of the variables described above.

T_{sc} = 530°R
P_{sc} = 14.7 psia
E = 0.92

$$d = e^{0.2016\left(\frac{\ln(q_{sc})}{0.51}+\ln\left(\frac{LT_mZ_m\lambda^{0.961}}{P_1^2-P_2^2}\right)-19.916\right)}$$

Where all the variables are defined previously.

The actual calculations of the parameters in this equation occur in the table at the bottom of the spreadsheet, below the Cost Calculations table. Each of the calculations is described in detail in the bullet points below.

- Mean Gas Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual.

- Mean Gas Relative Density (air = 1): Hydrogen gas has a mean gas density of 0.06897.

- Pipeline Flowrate: The pipeline flowrate, which is entered in kg/day at the top of the Design Inputs tab, is converted to standard cubic feet (scf)/day in this cell, and also increased based on the losses experienced during pipeline transmission.

$$F_{scf} = \frac{F_{kg}}{0.002363(1 - losses)}$$

Where 0.002363 is the conversion factor for kg of hydrogen to scf of hydrogen and:

F_{kg} = Peak Hydrogen Flowrate Out (from Design Inputs table)
losses = Hydrogen Losses During Pipeline Delivery (from Scenario Inputs table, and described later).

For the trunk and distribution pipelines, the total flowrate is divided by the number of pipelines, as specified in the Design Inputs table.

- Mean Temperature of Line: The calculation in this cell converts the temperature entered in the Design Inputs table from °C to °R.

- Pipeline Length: This item reads the pipeline length for transmission, trunk or distribution from the Design Inputs table.

- Input Pipeline Inlet Pressure: The calculation in this cell pulls the inlet pipeline pressures for the transmission, trunk or distribution from the Design Inputs table.

- Input Pipeline Outlet Pressure: The calculation in this cell pulls the outlet pipeline pressures for the transmission, trunk or distribution from the Design Inputs table.

- Pipeline diameter: The calculation in this cell uses the rearranged Panhandle B Pipeline equation to determine the diameter of the pipeline.

If the user selects ***no***, then he or she must enter values for diameters of the transmission, trunk and distribution pipelines in later cells. The labels in the cells requiring input will only appear if ***no*** is selected.

In this case, the Panhandle B equation has been rearranged to calculate the outlet pressure from the pipeline of specified diameter. The equation used is shown below.

$$P_2 = \sqrt{(P_1^2 - e^{1.961\ln(q_{sc}) - 20.366 - 4.961\ln(d) + 0.961\ln(\lambda) + \ln(L) + \ln(T_m) + \ln(Z_m)})}$$

Where all variables have been defined previously.

In the table at the bottom of the spreadsheet where the Panhandle B calculations are completed, cells in addition to those described above will appear.

- Inlet Pipeline Diameter: The calculation in this cell pulls the user-input pipeline diameters for the transmission, trunk or distribution from the Design Inputs table.

- Pipeline Outlet Pressure: The pipeline pressure, as calculated using the rearranged Panhandle B equation described above, will appear only if it is greater than the Desired Outlet Pressure (for either transmission, trunk or distribution) entered in the Design Inputs table. If it is less than the Desired Outlet Pressure, then "Undefined" will show up in this cell.

- Pipeline Outlet Pressure: This cell reads the value from the previous Pipeline Outlet Pressure cell.

- Transmission Pipeline Inlet Pressure: Enter the pressure at the inlet of the transmission pipeline. This entry can be left empty if the user is only looking at either a trunk or distribution pipeline, or a combination of trunk and distribution pipelines.

- Desired Transmission Pipeline Outlet Pressure: Enter the pressure at which the gas should exit the transmission pipeline length.

- Transmission Pipeline Temperature. The user should enter the temperature of the hydrogen gas in the transmission pipeline.

- Transmission Pipeline Length: The user needs to enter the length of the transmission pipeline used in the analysis.

- Transmission Pipeline Diameter. An input is required in this cell only if the user answered ***no*** to the question "Use H2A Calculations, using the Panhandle B Pipeline equation, to Calculate Pipeline Diameter". In that instance, the user needs to enter the diameter of the pipeline that is to be analyzed.

- Trunk Pipeline Inlet Pressure: Enter the pressure at the inlet of the trunk pipeline. This entry can be left empty if the user is only looking at either a transmission or distribution pipeline, or a combination of transmission and distribution pipelines. The trunk pipeline pressure can be lower than the transmission pipeline outlet pressure to account for pressure drops in valves or other devices.

- Desired Trunk Pipeline Outlet Pressure: Enter the pressure at which the gas should exit the trunk pipeline length.

- Trunk Pipeline Temperature. The user should enter the temperature of the hydrogen gas in the trunk pipeline.

- Number of Trunk Pipelines: The user should enter the number of lengths of trunk pipelines. A single transmission line may feed more than one trunk pipeline.

- Trunk Pipeline Length: The user needs to enter the length of each trunk pipeline.

- Distribution Pipeline Inlet Pressure: Enter the pressure at the inlet of the distribution pipeline. This entry can be left empty if the user is only looking at either a transmission or trunk pipeline, or a combination of transmission and trunk pipelines. The distribution pipeline pressure can be lower than the trunk pipeline outlet pressure to account for pressure drops in valves and other devices.

- Desired Distribution Pipeline Outlet Pressure: Enter the pressure at which the gas should exit the distribution pipelines.

- Distribution Pipeline Temperature. The user should enter the temperature of the hydrogen gas in the distribution pipeline.

- Number of Distribution Pipelines: The user should enter the number of lengths of distribution pipelines. Usually, a single trunk line will feed more than one distribution pipeline.

- Distribution Pipeline Length: The user needs to enter the length of each distribution pipeline (as entered in the previous cell) used in the analysis.

5.15.5 Scenario Inputs

- Hydrogen Loss During Pipeline Delivery: Enter, as a percentage of the feed flowrate, the amount of hydrogen that is lost in the pipeline distribution system.

5.15.6 Calculations

The majority of the calculations shown in this table are performed in the table where the answers to the rearranged Panhandle B equations are determined (at the bottom of the spreadsheet, below the Cost Calculations table).

- Transmission Pipeline Diameter: The value shown in this cell depends upon the answer to the question "Use H2A Calculations, using the Panhandle B pipeline equation, to calculate pipeline diameter?" in the Design Inputs table. If ***yes*** was selected, then the result from the Panhandle B equation that calculates diameter is fed to this cell. If ***no*** was selected, the user-input value is used (from Design Inputs table).

- Trunk Pipeline Diameter: The value shown in this cell depends upon the answer to the question "Use H2A Calculations, using the Panhandle B pipeline equation, to calculate pipeline diameter?" in the Design Inputs table. If ***yes*** was selected, then the result from the Panhandle B equation that calculates diameter is fed to this cell. If ***no*** was selected, the user-input value is used (from Design Inputs table).

- Distribution Pipeline Diameter: The value shown in this cell depends upon the answer to the question "Use H2A Calculations, using the Panhandle B pipeline equation, to calculate pipeline diameter?" in the Design Inputs table. If ***yes*** was selected, then the result from the Panhandle B equation that calculates diameter is fed to this cell. If ***no*** was selected, the user-input value is used (from Design Inputs table).

- Transmission Pipeline Velocity: The value in this cell is the actual velocity of the gas traveling through the transmission pipeline. It is calculated using the following formula.

$$v_{pipe,trans} = \left(\frac{14.7}{P_{trans,in}}\right)\left(\frac{F_{peak}}{\pi d_{trans}^{2}}\right)$$

Where:

$P_{trans,in}$ = Transmission Pipeline Inlet Pressure (from Design Inputs table)
F_{peak} = Peak Hydrogen Flowrate Out converted to ft^3/day (from Design Inputs table)
d_{trans} = Transmission Pipeline Diameter converted to ft.

- Trunk Pipeline Velocity: The value in this cell is the actual velocity of the gas traveling through the trunk pipeline(s). It is calculated using the following formula.

$$v_{pipe,trunk} = \left(\frac{14.7}{P_{trunk,in}}\right)\left(\frac{F_{peak}}{n_{trunk}\pi d_{trunk}^{2}}\right)$$

Where:

$P_{trunk,in}$ = Trunk Pipeline Inlet Pressure (from Design Inputs table)
F_{peak} = Peak Hydrogen Flowrate Out converted to ft^3/day (from Design Inputs table)
n_{trunk}= Number of Trunk Pipelines (from Design Inputs table)
d_{trunk} = Trunk Pipeline Diameter converted to ft.

- Distribution Pipeline Velocity: The value in this cell is the actual velocity of the gas traveling through the distribution pipeline(s). It is calculated using the following formula.

$$v_{pipe,dist} = \left(\frac{14.7}{P_{dist,in}}\right)\left(\frac{F_{peak}}{n_{dist}\pi d_{dist}^{2}}\right)$$

Where:

$P_{dist,in}$ = Distribution Pipeline Inlet Pressure (from Design Inputs table)
F_{peak} = Peak Hydrogen Flowrate Out converted to ft^3/day (from Design Inputs table)
n_{dist}= Number of Distribution Pipelines (from Design Inputs table)
d_{dist} = Distribution Pipeline Diameter converted to ft.

- Net Hydrogen Delivered: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 (days/yr).

The following cells will only appear if ***no*** was selected as the answer to the question "Use H2A Calculations, using the Panhandle B pipeline equation, to calculate pipeline diameter?" in the Design Inputs table.

- Tranmission Pipeline Outlet Pressure: The formula in this cell reads the resulting outlet pressure from the rearranged Panhandle B equation (calculating the outlet pressure). If the Desired Transmission Outlet Pressure is greater than the result from the Panhandle B equation, "Undefined" will show up in this cell.

- Trunk Pipeline Outlet Pressure: The formula in this cell reads the resulting outlet pressure from the rearranged Panhandle B equation (calculating the outlet pressure). If the Desired Trunk Outlet Pressure is greater than the result from the Panhandle B equation, "Undefined" will show up in this cell.

- Distribution Pipeline Outlet Pressure: The formula in this cell reads the resulting outlet pressure from the rearranged Panhandle B equation (calculating the outlet pressure). If the Desired Distribution Outlet Pressure is greater than the result from the Panhandle B equation, "Undefined" will show up in this cell.

5.15.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

5.15.8 Capital Investment

As mentioned previously, the H2A Delivery team has developed a cost curve that can estimate the capital cost of a hydrogen pipeline system. The data for the cost curve was taken from a study completed by Nathan Parker at the University of California Davis. The costs are broken down into four parts: pipeline material cost, labor cost, miscellaneous cost and right of way cost.

It is assumed that the costs associated with the installation of natural gas pipelines will be less than those for hydrogen pipelines, as materials of construction and weld-types may be different. In the model, the H2A Delivery team assumes that the hydrogen pipeline costs will be 10% higher than those for natural gas.

Plots showing the cost, in 2005 dollars, of these different parts of a pipeline installed cost are shown in the next several figures. These figures are on the "Pipeline Costs" tab at the end of the Components model.

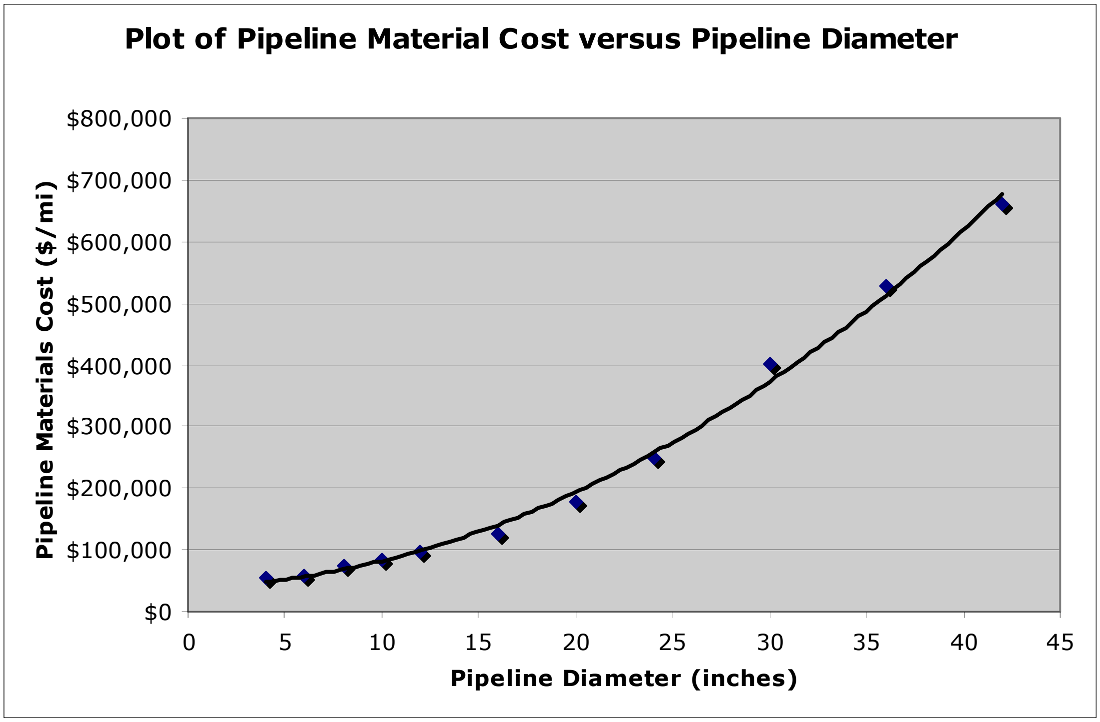

Figure 25. A plot showing the pipeline material cost as a function of pipeline diameter (Parker, 2005).

The curve fit gave the following equation for determining pipeline material cost. Note the 1.1 factor in the front of the equation, which is used to account for the 10% higher price for hydrogen pipelines. Also, please realize that the graph gives a cost in $/km, which was converted to give a cost in $/mi, as shown in the equation below.

$$Cost_{mat} = 1.1(330.5d^2 + 687d + 26{,}960)$$

Where the cost is on a per mile basis and d is the pipeline diameter (Parker, 2005).

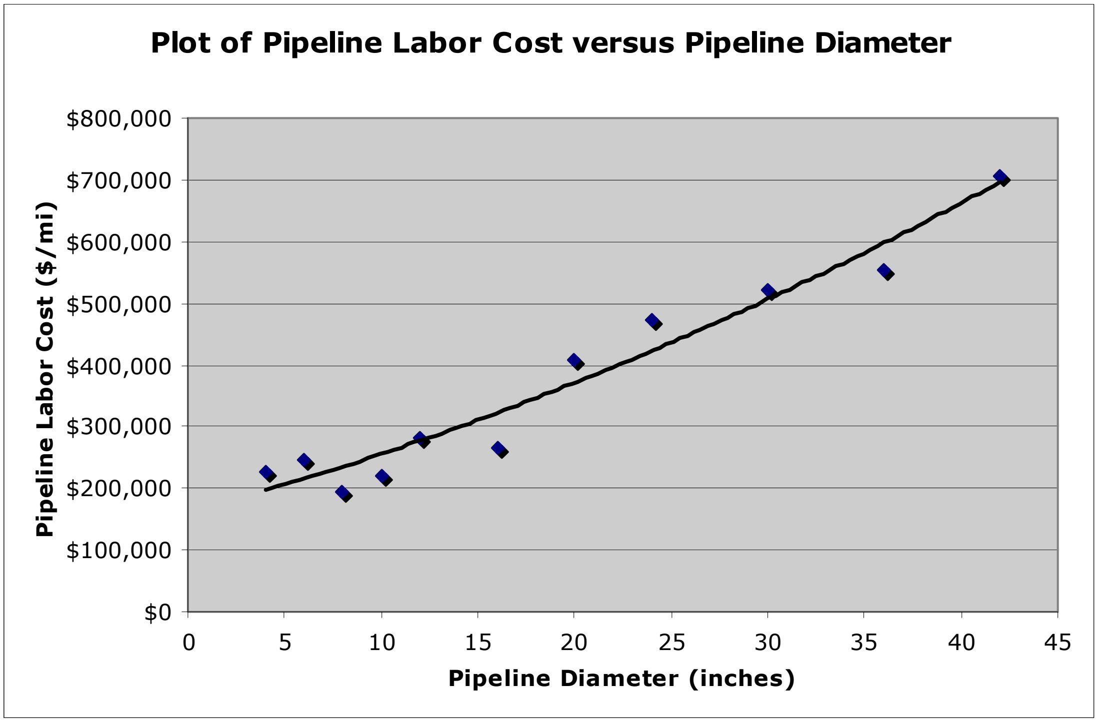

Figure 26. A plot showing the labor cost as a function of pipeline diameter (Parker, 2005).

The curve fit gave the following equation for determining labor cost. Note the 1.1 factor in the front of the equation, which is used to account for the 10% higher price for hydrogen pipelines. Also, please realize that the graph gives a cost in $/km, which was converted to give a cost in $/mi, as shown in the equation below.

$$Cost_{labor} = 1.1(343d^2 + 2{,}074d + 170{,}013)$$

Where the cost in is $/mi and d is the pipeline diameter (Parker, 2005).

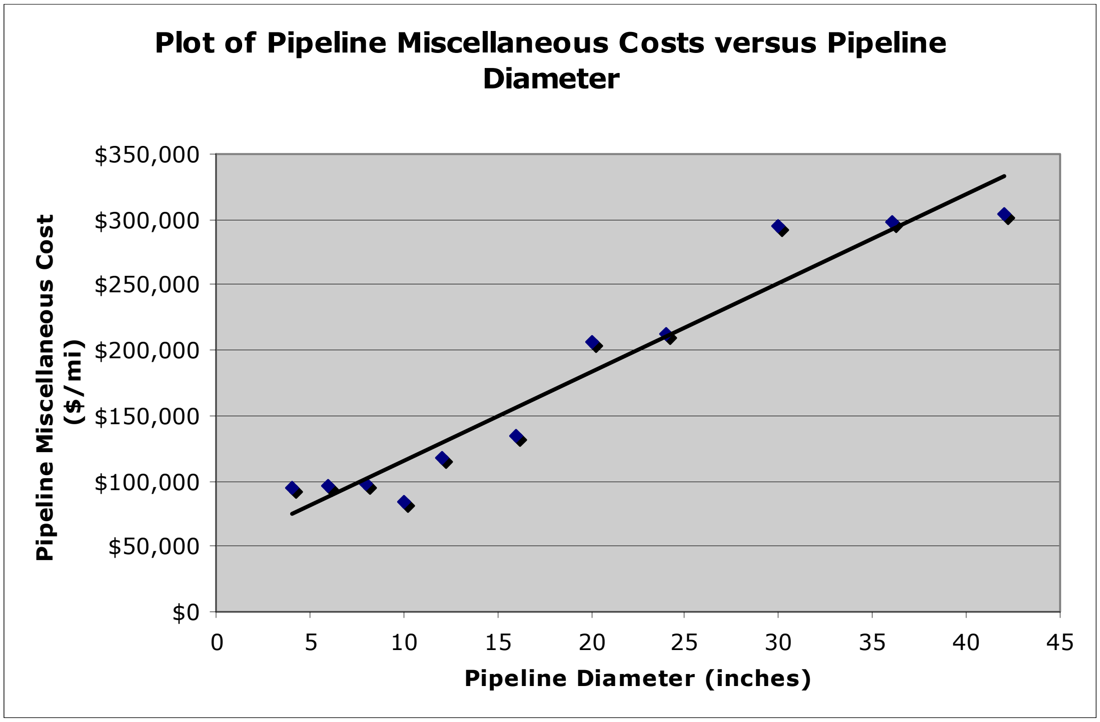

Figure 27. A plot showing the miscellaneous cost as a function of pipeline diameter (Parker, 2005).

The curve fit gave the following equation for determining miscellaneous cost. The miscellaneous costs include the following: surveys, engineering, supervision, interest, administration and overheads, contingencies, allowances for funds used during construction and FERC fees. Note the 1.1 factor in the front of the equation, which is used to account for the 10% higher price for hydrogen pipelines. Also, please realize that the graph gives a cost in $/km, which was converted to give a cost in $/mi, as shown in the equation below.

$$Cost_{misc} = 1.1(8{,}417d + 7{,}324)$$

Where the cost is in $/mi and d is the pipeline diameter (Parker, 2005).

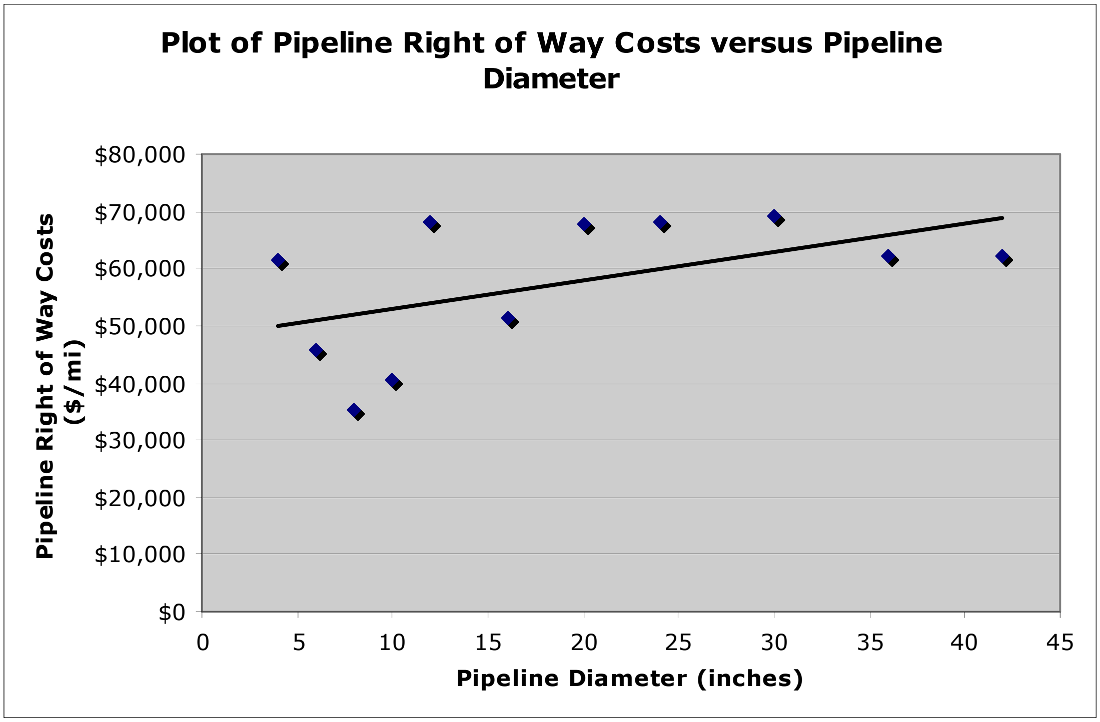

Figure 28. A plot showing the right of way cost as a function of pipeline diameter (Parker, 2005).

The curve fit gave the following equation for determining right of way cost. Note the 1.1 factor in the front of the equation, which is used to account for the 10% higher price for hydrogen pipelines. Also, please realize that the graph gives a cost in $/km, which was converted to give a cost in $/mi, as shown in the equation below.

$$Cost_{land} = 1.1(577d + 29{,}788)$$

Where the cost is in $/mi and d is the pipeline diameter (Parker, 2005).

The specific entries for this table are described below.

- Use the H2A Pipeline Costs…: The entry for this cell uses a yes/no toggle switch. If ***yes*** is selected, then:
  - The H2A pipeline cost functions, described above, are used to determine the pipeline capital cost. Not other entry is required in the Capital Cost table.

  If ***no*** is selected, then entry is required in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" columns for each of the items in the table.

- Distribution Pipeline: Pipeline length for the distribution pipeline system is taken from the entry in the Design Inputs table.

- Distribution Pipeline, Pipeline Material: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{mat} = Cost_{mat,/mile} L + 35{,}000$$

  Where:

  $Cost_{mat,/mile}$ = materials cost in \$/mi
  L = distribution pipeline length (from the Design Inputs table).

- Distribution Pipeline, Miscellaneous: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{misc} = Cost_{misc,/mile} L + 95{,}000$$

  Where:

  $Cost_{mis,/mile}$ = miscellaneous cost in \$/mi
  L = distribution pipeline length (from the Design Inputs table).

- Distribution Pipeline, Labor: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{lab} = Cost_{lab,/mile} L + 185{,}000$$

  Where:

  $Cost_{lab,/mile}$ = labor cost in \$/mi
  L = distribution pipeline length (from the Design Inputs table).

- Trunk Pipeline: Pipeline length for the trunk pipeline system is taken from the entry in the Design Inputs table.

- Trunk Pipeline, Pipeline Material: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{mat} = Cost_{mat,/mile} L + 35{,}000$$

  Where:

  $Cost_{mat,/mile}$ = materials cost in \$/mi
  L = trunk pipeline length (from the Design Inputs table).

- Trunk Pipeline, Miscellaneous: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{misc} = Cost_{misc,/mile} L + 95{,}000$$

  Where:

  $Cost_{mis,/mile}$ = miscellaneous cost in \$/mi
  L = trunk pipeline length (from the Design Inputs table).

- Trunk Pipeline, Labor: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{lab} = Cost_{lab,/mile} L + 185{,}000$$

  Where:

  $Cost_{lab,/mile}$ = labor cost in \$/mi
  L = trunk pipeline length (from the Design Inputs table).

- Transmission Pipeline: Pipeline length for the transmission pipeline system is taken from the entry in the Design Inputs table.

- Transmission Pipeline, Pipeline Material: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{mat} = Cost_{mat,/mile} L + 35{,}000$$

  Where:

  $Cost_{mat,/mile}$ = materials cost in \$/mi
  L = transmission pipeline length (from the Design Inputs table).

- Transmission Pipeline, Miscellaneous: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{misc} = Cost_{misc,/mile} L + 95{,}000$$

  Where:

  $Cost_{mis,/mile}$ = miscellaneous cost in \$/mi
  L = transmission pipeline length (from the Design Inputs table).

- Transmission Pipeline, Labor: If the user opted to use the H2A pipeline costs, no entry is required in this row. Otherwise, the user needs to enter values in the "User Input Installed Cost" column, or both the "User Input Uninstalled Cost" column and the "Installation Cost Factor" column.

  If the user opted to use the H2A pipeline costs, then the following correlation is used to determine the Calculated Installed Cost.

  $$Cost_{lab} = Cost_{lab,/mile} L + 185{,}000$$

  Where:

  $Cost_{lab,/mile}$ = labor cost in \$/mi
  L = transmission pipeline length (from the Design Inputs table).

- Balance of Component: This item includes any other equipment that might be required for operation of a pipeline that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs. The values entered in this table allow the determination of a total capital investment.

- <u>Use H2A right of way/land cost…?</u>: Please select ***yes*** or ***no*** from the toggle switch.

  If the user selects ***yes***, then the right of way cost correlation is used, and no other entry is required for the land costs..

  If the user selects ***no***, then he or she needs to enter values for the land cost in the cells that appear in the table.

- <u>Distribution Pipeline Right of Way/Land Cost</u>: A value will only show in this cell if the user opted to use the H2A right of way/land costs. The following formula is used to calculate the distribution right of way cost.

  $$Cost_{land} = Cost_{land,/mile} L + 40{,}000$$

  Where:

  $Cost_{land,/mile}$ = right of way/land cost in \$/mi
  L = distribution pipeline length (from the Design Inputs table).

- <u>Trunk Pipeline Right of Way/Land Cost</u>: A value will only show in this cell if the user opted to use the H2A right of way/land costs. The following formula is used to calculate the trunk right of way cost.

  $$Cost_{land} = Cost_{land,/mile} L + 40{,}000$$

  Where:

  $Cost_{land,/mile}$ = right of way/land cost in \$/mi
  L = trunk pipeline length (from the Design Inputs table).

- <u>Transmission Pipeline Right of Way/Land Cost</u>: A value will only show in this cell if the user opted to use the H2A right of way/land costs. The following formula is used to calculate the transmission right of way cost.

  $$Cost_{land} = Cost_{land,/mile} L + 40{,}000$$

  Where:

  $Cost_{land,/mile}$ = right of way/land cost in \$/mi
  L = transmission pipeline length (from the Design Inputs table).

The user only needs to enter values in the following cells if they selected ***no*** to the question "Use H2A right of way/land costs…?".

- <u>Distribution Pipeline Right of Way/Land Cost:</u> The user needs to enter the distribution pipeline right of way/land costs because they selected ***no*** to the question "Use H2A right of way/land costs…?".

- Trunk Pipeline Right of Way/Land Cost: The user needs to enter the trunk pipeline right of way/land costs because they selected ***no*** to the question "Use H2A right of way/land costs…?".

- Transmission Pipeline Right of Way/Land Cost: The user needs to enter the transmission pipeline right of way/land costs because they selected ***no*** to the question "Use H2A right of way/land costs…?".

- Total Land Capital Cost: The transmission, trunk and distribution right of way/land costs are totaled in this table.

- Total Capital: The Total Land Capital Costs is summed with the Total Initial Capital Investment to determine this number.

5.15.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the hydrogen pipeline are entered. The table is divided into two sections: labor, and the remainder of costs. The user needs to remember that the pipeline does not have energy requirements, as a compressor is not included. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: The user should enter the total labor-hours per year required to operate the pipeline.

- Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work during the hours specified in the previous cell.

- Total Labor Cost: The labor requirement is multiplied by the labor cost to determine this value.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.

- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the pipeline.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

5.15.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, and other O&M costs for each part of the pipeline (transmission, trunk and distribution) are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

6.0 Mini-Scenario, or Combined Tabs in the Hydrogen Delivery Components Model

The tabs explained in this section are the mini-scenario tabs. They include combinations of the single component tabs already described.

6.1 Forecourt Station – Gaseous Hydrogen

This tab is used to calculate the contribution to the delivered hydrogen cost for a forecourt station where the hydrogen is delivered in a gaseous form. The tab assumes that the hydrogen is not produced at the forecourt. A forecourt station needs to be able to accept the gaseous hydrogen (delivered by a compressed gas tube trailer or by pipeline) and deliver it to a vehicle. To get the hydrogen onto the vehicle, the forecourt station is assumed to include the following:

- Gaseous storage
- Forecourt compressor(s)
- Hydrogen dispenser(s)

A simplified process flow diagram of a compressed gas hydrogen forecourt station is shown in Figure 29.

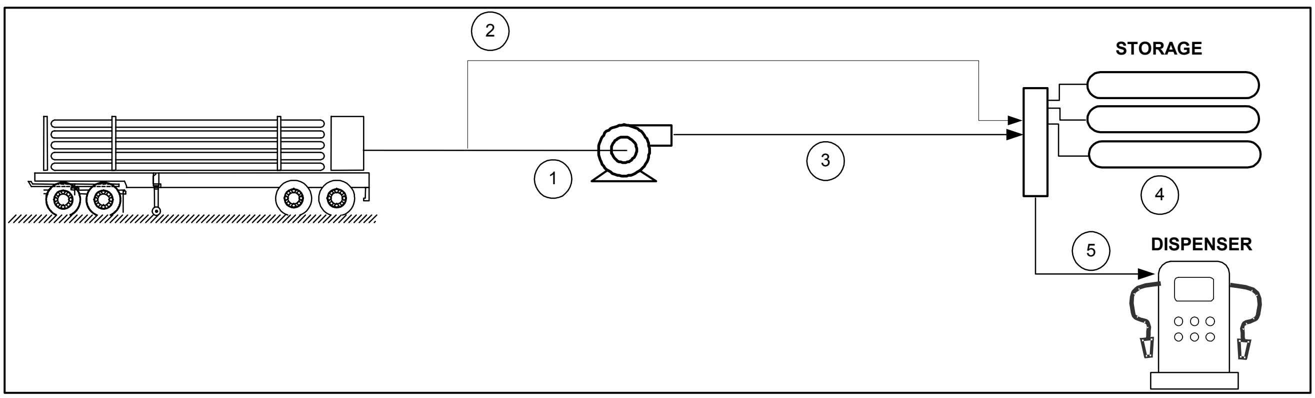

Figure 29. Simplified process flow diagram of a compressed gas hydrogen forecourt station.

The forecourt station – gaseous hydrogen tab is basically a combination of the forecourt compressor tab, H2 dispenser tab and the forecourt storage tab. Thus, in some areas in this section, the user will be referred to specific sections in the write-up for the other two tabs.

6.1.1 Design Concept

The forecourt station – gaseous hydrogen tab is designed to cost a combination of gaseous storage, forecourt compressor(s) and hydrogen dispenser(s) that can take delivered compressed gas hydrogen and fill the onboard storage tank in a vehicle. In H2A, a 100 kg/day station is used as a small station, and a 1,500 kg/day station is used as a large station. As many of the entries and calculations reference either a 100 or 1500 kg/day facility, it is not possible for the user to look at other sizes.

The model assumes that the compressed hydrogen gas is delivered to the station either by a standard current compressed gas tube trailer or by pipeline. The compressed gas tube-trailer, which is assumed to be dropped off at the forecourt station (serves as its own on-site storage tank), will only serve the 100 kg/day station. Current compressed hydrogen tube trailers (maximum fill pressure of 2,700 psi) can hold approximately 300 kg of hydrogen. If this tube trailer was used in a 1,500 kg/day station, the trailer would need to be replaced 5 times a day, which could be a logistical problem. Therefore, only a pipeline is assumed to delivery compressed gas hydrogen to a 1,500 kg/day station. Provisions for a higher pressure (7000 psi) tube trailer delivery for a 1500 kg/day station will be added to the model at a later date.

In the 100 kg/day station, as mentioned previously, the compressed gas hydrogen trailer is assumed to be dropped off and left at the station. Therefore, a large compressed gas storage system is not required. The hydrogen from the trailer is compressed, using a forecourt compressor, to a cascading dispensing system, and delivered to the vehicle through the hydrogen dispenser. The size of the storage for the cascade dispensing system is 38 kg of hydrogen. During operation, the pressure in the compressed gas tube trailer will continually decrease. The compressor needs to be designed to accept the minimum pressure in the trailer, and compress to the filling pressure. However, it will not always operate at this maximum condition, which is considered when the annual energy requirement for the station is calculated (described in more detail below).

The 1,500 kg/day station is designed very similar to the 100 kg/day station. The only storage required onsite is for the cascade filling system (the pipeline serves as storage). The compressor in this instance will always have a constant suction pressure (pipeline pressure) and a constant outlet pressure.

As mentioned in other sections, the compressor units are spared in many hydrogen applications to ensure a high level of operational availability. To this end, the tab allows the user to enter the number of purchased compressors along with the number of compressors operating at any one time.

6.1.2 Key Assumptions

- Only 1,500 kg/day and 100 kg/day stations are modeled. The tab cannot handle any other size forecourt stations.
- In the 100 kg/day case, the hydrogen is delivered by a current compressed gas tube trailer (2700 psi), which is dropped off and serves as onsite storage.
- In the 1,500 kg/day case, the hydrogen is delivered by a pipeline.
- The station operates at a 70% capacity factor.
- The user needs to know either the number of stages in the compressor or the compression ratio per stage. In selecting these values, the user must ensure that typical material

temperature constraints are not exceeded, as the model does not check interstage or exit temperatures.

- The theoretical power requirement calculation assumes that the compression work is equally divided between the stages and that an intercooler between each stage brings the gas temperature back to the original inlet temperature.

- It is assumed that there are no pressure drops in the after-cooler or interstage coolers.

- An electrical-powered compressor is assumed. The tab does not allow for the calculation of costs associated with compressors fed with other fuels such as natural gas or hydrogen.

6.1.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Forecourt Station Definitions table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

2. No capital costs are entered.

6.1.4 Forecourt Station Definitions Inputs

Entries made in this table define the type of station that the user will be investigating. There are error messages that appear to the right of the table so that the user can see if an incorrect entry has been made. It is important to remember that only 100 kg/day and 1,500 kg/day stations can be analyzed.

- Select Mechanism of Delivery for the Gaseous Hydrogen: Please use the toggle switch to select either gaseous-truck or gaseous-pipeline. The model is set-up so that a gaseous truck can only be used for a 100 kg/day station, whereas a pipeline can be used for either a 100 kg/day or a 1,500 kg/day station.

- Select the Design Capacity of the Forecourt Station: Please use the toggle switch to select either 100 or 1,500. If a user selects gaseous-truck in the prior cell, and then chooses 1,500, an error message will appear.

6.1.5 Design Inputs

The design inputs table is for the user to enter various values that are important for sizing the compressed gas forecourt station. This table contains a number of yes/no toggle switches, which enhance the flexibility of the model. As this tab includes components that have their tabs, the user may be directed to look at other parts of this manual for information. The items included in this table are described below.

- Average Hydrogen Out: The value that shows up in this cell depends on the entry in the cell "Select the Design Capacity of the Forecourt Station". Since the capacity factor is fixed at 70%, 70 will show up if 100 was selected, whereas 1,050 will show up if 1,500 was entered.

- Peak Hydrogen Flowrate Out: The value shown is taken from the "Select the Design Capacity of the Forecourt Station" cell.

- Capacity Factor: The capacity factor for this tab is fixed at 70%.

- Maximum Pressure in the Tube Trailer: Entry is only required in this cell if the user selected "gaseous-truck" in the Forecourt Station Definitions table. In that case, the user needs to enter the maximum pressure of the delivered hydrogen in a tube trailer.

- Minimum Pressure in the Tube Trailer: Entry is only required in this cell if the user selected "gaseous-truck" in the Forecourt Station Definitions table. In that case, the user needs to enter the the pressure at which the tube trailer is considered to be empty. Remember that this pressure will not be 14.7 psia because the tank is never completely emptied.

- Pressure of the Hydrogen Delivered to the Forecourt Station: Entry is only required in this cell if the user selected "gaseous-pipeline" in the Forecourt Station Definitions table. In that case, the user needs to enter the pipeline pressure at the gate to the forecourt station.

- Dispensing Pressure: The user should enter the pressure at which the hydrogen will be delivered from the dispenser.

- Hydrogen Temperature at Station: Enter the temperature of the hydrogen gas at the forecourt station.

- Use H2A Estimations for the Number of Dispensers?: The user needs to select either ***yes*** or ***no***.

  If ***yes*** is selected, then the number of dispensers will be calculated assuming that each unit has a capacity of 500 kg/day.

  If ***no*** is selected, then the user can enter the number of dispensers required.

- Enter Number of Dispensers Required: This cell only requires input if the user answered ***no*** to the question "Use H2A Estimations for the Number of Compressors?". In that case, the user needs to enter the number of dispensers required.

- The rest of the cells are used in sizing the compressors. Please see the Design Inputs description for the Forecourt Compressor to get specific information on what should be entered in these cells.

6.1.6 Calculations

- Gas Contant: The standard value of 8.3144 kJ/K.kg_mol is used in the H2A Delivery case.

- Mean Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual.

- Design Tank Useable Capacity: The number in this cell corresponds to the size of the storage vessels for the cascade filling system, and depends on whether the user selected a 100 or 1,500 kg/day station. If a 100 kg/day station was selected, then 38 kg of storage are required. If a 1,500 kg/day station was selected, then 358 kg of storage are required.

- Tank Water Volume: This calculation refers to the size of the compressed gas hydrogen cascade storage system. The result of the calculation used in this cell is for informational purposes only. The volume is calculated according to the following equation.

  $$V = \frac{C_{des} Z T_{oper} R}{P_{\max}}$$

  Where all the variables have been defined previously in this section except:

  C_{des} = Design Tank Useable Capacity, converted to moles of hydrogen
  T_{oper} = operating temperature, converted to K (from Design Inputs table)
  R = gas constant, 8.2x10-5 psi/mol.K.

- Number of Dispensers: If ***yes*** was selected to the question "Use H2A Estimations for the Number of Dispensers?", then the value shown in this cell is calculated by dividing the Peak Hydrogen Flowrate Out by 500 kg/day, and then rounding up the result.

  If ***no*** was selected, then the value shown in this cell is taken from the input to Enter the Number of Dispensers Required.

- The calculations in the next four cells are described in the forecourt compressor tab calculations section portion of this manual. The idealized power calculation is described in the general comments section of this document.

- Net Hydrogen Delivered: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 days/year.

6.1.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

6.1.8 Capital Investment

This table is where the capital costs for the specific components in the forecourt station are entered. As with other tabs, the H2A Delivery team has put together some capital cost functions, which are described below.

- Use H2A Forecourt Team Costs for Compressors?: Please use the toggle switch to enter ***yes*** or ***no***. The H2A Forecourt Team uses an estimation of $4,580/(kg/hr of hydrogen) installed for a piston compressor to raise the pressure from 20 atm to 425 atm for the 1,500 kg/day station. If a 100kg/day station is required, the installed compressor cost is $6,300/(kg/hr of hydrogen) for a piston with the same inlet/outlet pressures..

- Use H2A Dispenser Costs?: Please use the toggle switch to enter ***yes*** or ***no***. The H2A Forecourt Team uses an installed cost of $26,880 per dispenser.

- Use H2A Forecourt Compressed Gas Storage Costs?: Please use the toggle switch to enter ***yes*** or ***no***. The correlation taken from the H2A forecourt team is as follows: Capital Cost (installed) = 818*(Design Tank Capacity (kg)). This cost is based on ASME metal cylinders holding 14kg each at 6250psi. Includes peripherals and mounting structures.

If the user selects ***no*** to any of the questions above, then he or she will need to enter their own capital costs.

The rest of the cells in this table are described below.

- Number of Compressor Units: This value is linked to the number of compressors required, which was specified in the Design Inputs table.

- Hydrogen Flowrate per Unit: This value is determined by dividing the Design Flowrate to Each Compressor (from the Calculations Table) by 24 (hrs/day).

  If the user answered ***yes*** to the question "Use H2A Forecourt Team Costs for Compressors", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Number of Dispensers: This value is taken from the Calculations Table.

  If the user answered ***yes*** to the question "Use H2A Dispenser Costs", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Overall Safety and Control Equipment: This equipment is required in operating a compressed gas forecourt station. The user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns

- Balance of Component: This item includes any other equipment that might be required for operation of a compressed gas forecourt station that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment.

- Land Required: Please enter the amount of land required for the compressed hydrogen forecourt station. Please note that in the base H2A cases, it is assumed that the land for the forecourt station is rented.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of these compressors.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Capital Investment: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

6.1.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the liquid forecourt station are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Maintenance Labor Required: The user should enter the total labor-hours per year required to maintain the forecourt station.

- Forecourt Station Labor Required: The forecourt station labor specified in this cell refers to a person who works in the "kiosk" collecting money. The value that appears depends on whether the user selected the 100 kg/day station or the 1,500 kg/day station. For both the 100 and 1,500 kg/day facilities, it is assumed that the station operates 18 hours per day and 365 days per year. Of that required labor, it is assumed that 50% is allocated to fuel sales. For the 100 kg/day station, it is further assumed that 1 out of the 8 dispensers at a forecourt station deliver hydrogen. For the 1,500 kg/day station, it is assumed that 3 out of the 8 dispensers are delivering hydrogen.

- Maintenance Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to perform maintenance on the forecourt station during the hours specified previously.

- Forecourt Station Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work in the "kiosk" at a forecourt station during the hours specified previously.

- Total Labor Cost: The total labor cost is determined by multiplying the Maintenance Labor by the Maintenance Labor Cost, and then adding the result to the product of the Forecourt Station Labor Requirement and the Forecourt Station Labor Cost.

The annual energy requirement for the compressor is different from the theoretical value calculated in the Calculations table. During a typical operating year, the feed flowrate to the compressor will fluctuate. Therefore, the average hydrogen flowrate out is used as a basis to calculate the annual energy requirement (see the beginning of this manual for a discussion of peak and average flowrates).

If the user opted to use the idealized power equation, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 \frac{F_{avg}}{\eta_{isentrop}} ZRT_1 N_{st} \left(\frac{k}{k-1} \right) \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{kN_{st}}} - 1 \right]$$

Where:

$\eta_{isentrop}$ = isentropic compressor efficiency (from Design Inputs table)
F_{avg} = average hydrogen flowrate out, converted to mol/sec (from Design Inputs table)
R = gas constant (specified in the Calculation table)
T_1 = inlet gas temperature, converted to K (from Design Inputs table)
N_{st} = number of compression stages (calculated in the Calculations table)
k = ratio of specific heats (specified as Cp/Cv in the Design Inputs table)
p_2 = outlet pressure (specified in the Design Inputs table)
p_1 = inlet pressure (specified in the Design Inputs table).

If the user selected a gaseous truck to deliver the hydrogen, then p_1 is determined by taking the logarithmic mean of the maximum and minimum pressures in the tank. The suction pressure to the compressor will vary as the pressure in the tank decreases, and this needs to be considered when calculating the inlet pressure. The formula for calculating the logarithmic mean is shown below.

$$p_1 = \frac{p_{\max} - p_{\min}}{\ln\left(\frac{p_{\max}}{p_{\min}} \right)}$$

Where:

p_{max} = maximum tube trailer pressure (specified in the Design Inputs table)
p_{min} = minimum tube trailer pressure (specified in the Design Inputs table).

If the user selected a pipeline to delivery the hydrogen, then p_1 is simply the pipeline outlet pressure.

If the user opted to specify a compressor power requirement per kg/hr of hydrogen, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 P_{req} \frac{F_{avg}}{24}$$

P_{req} = Power requirement per kg/hr of hydrogen (from Design Inputs table)
F_{avg} = average hydrogen flowrate out (from Design Inputs table).

As described in a previous section, the user can either enter their own cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total utility cost is determined by multiplying either the user-input fuel cost or the H2A value by the Annual Energy Requirement.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.

- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The value that is calculated in this cell is the annual rent. The value that appears depends on the design capacity of the station. If the user selected a 1,500 kg/day station, then the annual rent cost, based upon H2A Forecourt team calculations, is $24,162/year. If the user selected a 100 kg/day station, then the annual rent is $15,594, again based on H2A Forecourt team calculations.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom of the table.

6.1.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the compressed gas forecourt station are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

6.2 Forecourt Station – Liquid

This tab is used to calculate the contribution to the delivered hydrogen cost for a forecourt station where the hydrogen is delivered in liquid form. The tab assumes that the hydrogen is not produced at the forecourt. A forecourt station needs to be able to accept the liquid hydrogen (delivered by a trailer) and deliver it to a compressed gas onboard vehicle storage system. To get the hydrogen onto the vehicle, the forecourt station is assumed to include the following:

- Liquid storage
- Gaseous storage
- Low temperature liquid pump(s)
- Hydrogen dispenser(s)

A simplified process flow diagram of a liquid hydrogen forecourt station is shown in Figure 30.

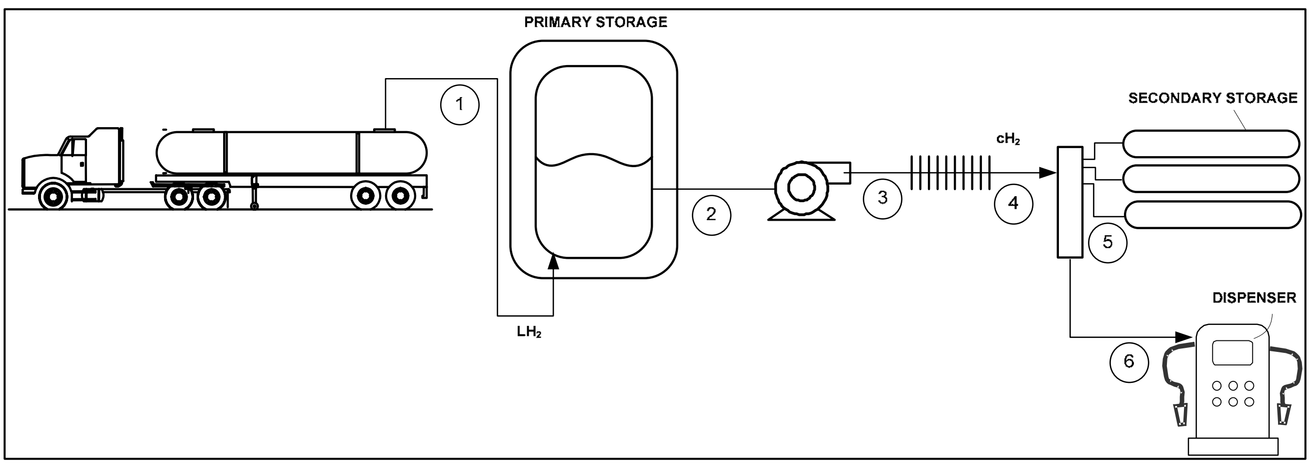

Figure 30. Simplified process flow diagram of a liquid hydrogen forecourt station.

The forecourt station – liquid hydrogen tab is basically a combination of the bulk liquid hydrogen storage tab, the H2 dispenser tab and the forecourt storage tab. Thus, in some areas in this section, the user will be referred to specific sections in the write-up for those other tabs.

6.2.1 Design Concept

The forecourt station – liquid tab is designed to cost a combination of gaseous storage, liquid hydrogen storage, low temperature liquid pump(s) and hydrogen dispenser(s) that can take delivered liquid hydrogen and charge gaseous hydrogen to a vehicle. In H2A, a 100 kg/day station is used as a small station, and a 1,500 kg/day station is used as a large station. The same station sizes are assumed for this forecourt station tab. As many of the entries and calculations reference either a 100 or 1500 kg/day facility, it is not possible for the user to look at other sizes.

The model assumes that the liquid hydrogen is delivered to the station by a cryogenic liquid hydrogen trailer. Unlike the compressed gas forecourt station, however, the trailer is not left on site. Rather, there is a liquid storage tank at the station to hold the liquid hydrogen. If a 100 kg/day station is used, then it is assumed that the trailer drops off 1/3 of its liquid hydrogen (if you recall from the Truck-LH2 Delivery tab, the trailer can make a maximum of 3 stops, delivering 1/3 of its load to each station). If a 1,500 kg/day station is used, then the entire liquid hydrogen load in a trailer is dropped at the station. A current liquid hydrogen trailer holds slightly less than 4,000 kg of hydrogen.

In the 100 kg/day station, a liquid hydrogen storage tank to hold 1/3 of a full liquid hydrogen tanker is located onsite to store the liquid hydrogen. This liquid hydrogen is then pumped to delivery pressure, and vaporized before being stored into a compressed gas cascade dispensing system. The size of the storage for the cascade dispensing system is 38 kg of hydrogen. The hydrogen, now in gaseous form, is then loaded onto vehicles form the cascade dispensing system.

The 1,500 kg/day station is designed very similar to the 100 kg/day station. The primary difference is the size of the compressed gas and liquid storage systems. A mentioned previously, a full load of liquid hydrogen is delivered to the station in this case. Therefore, the onsite liquid storage tank needs to be capable of holding that amount of hydrogen. The compressed gas storage for the cascade dispensing system in this case is 358 kg of hydrogen.

6.2.2 Key Assumptions

- Only 1,500 kg/day and 100 kg/day stations are modeled. The tab cannot handle any other size forecourt stations.
- In the 100 kg/day case, the hydrogen delivered is equivalent to 1/3 of a full liquid hydrogen tanker (see the Truck-LH2 Delivery tab).
- In the 1,500 kg/day case, the hydrogen delivered is equivalent to a full liquid hydrogen tanker (see the Truck-LH2 Delivery tab).
- The station operates at a 70% capacity factor.
- Electrical-powered low temperature pumps are assumed.
- Other than the pumps, the electrical/fuel requirement for all other pieces of equipment are assumed to be negligible.

6.2.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Liquid Forecourt Station Definitions table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

6.2.4 Design Inputs

The design inputs table is for the user to enter various values that are important for sizing the liquid hydrogen forecourt station. As this tab includes components that have their tabs, the user may be directed to look at other parts of this manual for information. The items included in this table are described below.

- Average Hydrogen Out: The value that shows up in this cell depends on the entry in the cell "Peak Forecourt Station Demand" (next cell). Since the capacity factor is fixed at 70%, 70 will show up if 100 is selected, whereas 1,050 will show up if 1,500 is entered.
- Peak Hydrogen Flowrate Out: Please use the toggle switch to select either 1,500 kg/day or 100 kg/day.
- Capacity Factor: The capacity factor for this tab is fixed at 70%.
- Dispensing Pressure: The user should enter the pressure at which the hydrogen will be delivered from the dispenser.
- Compressed Gas Storage Temperature: Enter the temperature of the hydrogen gas at the in the cascade refilling system. The liquid hydrogen is vaporized, and then stored in this system.
- Use H2A Estimations for the Number of Dispensers?: The user needs to select either ***yes*** or ***no***.

  If ***yes*** is selected, then the number of dispensers will be calculated assuming that each unit has a capacity of 500 kg/day.

  If ***no*** is selected, then the user can enter the number of dispensers required.
- Enter Number of Dispensers Required: This cell only requires input if the user answered ***no*** to the question "Use H2A Estimations for the Number of Compressors?". In that case, the user needs to enter the number of dispensers required.
- Storage Tank Boil-off: During storage, a portion of the liquid hydrogen will boil-off and be vented through a relief value on the vessel. This value should be entered as a percentage loss per day, based on the total volume of the storage system.

6.2.5 Calculations

- Gas Contant: The standard value of 8.3144 kJ/K.kg_mol is used in the H2A Delivery case.

- Mean Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual.

- Desired Liquid Cryogenic Tank Capacity: The number in this cell corresponds to the size of the vessels for storing the liquid hydrogen that is delivered to the station, and depends on whether the user selected a 100 or 1,500 kg/day station. If a 100 kg/day station was selected, then 1,496 kg of storage are required. If a 1,500 kg/day station was selected, then 4,488 kg of storage are required.

- The next two cells are used to determine the size of the liquid storage tanks. Please see the Bulk Liquid Hydrogen Storage tab for a description of the cell calculations (see the Calculations Table section).

- Design Tank Useable Capacity: The number in this cell corresponds to the size of the storage vessels for the cascade filling system, and depends on whether the user selected a 100 or 1,500 kg/day station. If a 100 kg/day station was selected, then 38 kg of storage are required. If a 1,500 kg/day station was selected, then 358 kg of storage are required.

- Tank Water Volume: The volume of the forecourt compressed gas storage tanks are calculated in this cell. The result of the calculation used in this cell is for informational purposes only. The volume is calculated according to the following equation.

  $$V = \frac{C_{des} Z T_{oper} R}{P_{\max}}$$

  Where all the variables have been defined previously in this section except:

  C_{des} = Design Tank Useable Capacity, converted to moles of hydrogen
  T_{oper} = operating temperature, converted to K (from Design Inputs table)
  R = gas constant, 8.2x10-5 psi/mol.K.

- Number of Dispensers: If ***yes*** was selected to the question "Use H2A Estimations for the Number of Dispensers?", then the value shown in this cell is calculated by dividing the Peak Hydrogen Flowrate Out by 500 kg/day, and then rounding up the result.

  If ***no*** was selected, then the value shown in this cell is taken from the input to Enter the Number of Dispensers Required.

- Liquid Pumps Required: It is assumed that the high pressure cryogenic liquid pump is spared. Therefore, 2 is shown in this cell.

- Liquid Pump Capacity: The number in this cell corresponds to the capacity of each high pressure liquid pump, and depends on whether the user selected a 100 or 1,500 kg/day station. If a 100 kg/day station was selected, then the required pump capacity is 6.7 kg of hydrogen per hour. If a 1,500 kg/day station was selected, then the required pump capacity is 100 kg of hydrogen per hour.

- Net Hydrogen Delivered: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 days/year.

6.2.6 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section.

6.2.7 Capital Investment

This table is where the capital costs for the specific components in the forecourt station are entered. As with other tabs, the H2A Delivery team has put together some capital cost functions, which are described below.

- Use H2A Costs for Liquid Hydrogen Cryogenic Storage Tank?: Please use the toggle switch to enter ***yes*** or ***no***. The H2A Forecourt Team got quotes for small LH2 storage tanks of ~$50/kg of H2 installed for a tank capacity of ~4000 kg of H2 and ~$140/kg of H2 installed for a tank capacity of ~620 kg of H2. For this model, the H2A Delivery team has opted to use an installed cost of $50/kg tanks serving 1500 kg/day stations and $70/kg for tanks serving 100 kg/day stations. We are assuming that 1/3 of our standard liquid delivery truck capacity is delivered to a 100 kg/day station, which means approximately 1,500 kg of liquid storage is required.

- Use H2A Dispenser Costs?: Please use the toggle switch to enter ***yes*** or ***no***. The H2A Forecourt Team uses an installed cost of $26,880 per dispenser.

- Use H2A Forecourt Compressed Gas Storage Costs?: Please use the toggle switch to enter ***yes*** or ***no***. The correlation taken from the H2A forecourt team is as follows: Capital Cost (installed) = 818*(Design Tank Capacity (kg)). This cost is based on ASME metal cylinders holding 14kg each at 6250psi. Includes peripherals and mounting structures.

- Use H2A Forecourt Evaporator Costs?: Please use the toggle switch to enter ***yes*** or ***no***. The H2A Forecourt Team uses an installed cost of $7,920 for an evaporator in the 100 kg/day facility, while the installed cost is $12,988 for the 1,500 kg/day facility.

- Use the H2A Forecourt High Pressure Cryogenic Pump Costs?: Please use the toggle switch to enter ***yes*** or ***no***. The H2A Forecourt Team uses an installed cost of $22,607 for a liquid pump in the 100 kg/day facility, while the installed cost is $29,638 for the 1,500 kg/day facility. These pumps are rated to 6,250 psia.

If the user selects no to any of the questions above, then he or she will need to enter their own capital costs.

The rest of the cells in this table are described below.

- Liquid Hydrogen Cryogenic Storage Tank, Capacity: This value is taken from the Calculations Table.

  If the user answered ***yes*** to the question "Use H2A Forecourt Team Costs for Liquid Hydrogen…", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Number of Dispensers: This value is taken from the Calculations Table.

  If the user answered ***yes*** to the question "Use H2A Forecourt Dispenser Costs", then no input is required in this row. Otherwise, the user either needs to enter a cost under "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Gaseous Storage, Capacity: This value is taken from the Calculations Table.

  If the user answered ***yes*** to the question "Use H2A Forecourt Team Costs for Compressed Gas Storage Costs", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Evaporator: One evaporator is required at the liquid forecourt station.

  If the user answered ***yes*** to the question "Use H2A Forecourt Team Evaporator Costs" then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Number of Pumps: This value is taken from the Calculations Table.

  If the user answered ***yes*** to the question "Use H2A Forecourt High Pressure Pump Costs", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Overall Safety and Control Equipment: This equipment is required in operating a liquid forecourt station. The user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns

- Balance of Component: This item includes any other equipment that might be required for operation of a compressed gas forecourt station that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment.

- Land Required: Please enter the amount of land required for the liquid hydrogen forecourt station. Please note that in the base H2A cases, it is assumed that the land for the forecourt station is rented.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design that accompanies the installation of the liquid forecourt station.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Capital Investment: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

6.2.8 Operating and Maintenance Costs

In this table, the annual costs required for operating the liquid forecourt station are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Maintenance Labor Required: The user should enter the total labor-hours per year required to maintain the forecourt station.
- Forecourt Station Labor Required: The forecourt station labor specified in this cell refers to a person who works in the "kiosk" collecting money. The value that appears depends on whether the user selected the 100 kg/day station or the 1,500 kg/day station. For both the 100 and 1,500 kg/day facilities, it is assumed that the station operates 18 hours per day and 365 days per year. Of that required labor, it is assumed that 50% is allocated to fuel sales. For the 100 kg/day station, it is further assumed that 1 out of the 8 dispensers at a forecourt station deliver hydrogen. For the 1,500 kg/day station, it is assumed that 3 out of the 8 dispensers are delivering hydrogen.
- Maintenance Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to perform maintenance on the forecourt station during the hours specified previously.
- Forecourt Station Labor Cost: This value, entered by the user, is for the unloaded labor rate for a person to work in the "kiosk" at a forecourt station during the hours specified previously.
- Total Labor Cost: The total labor cost is determined by multiplying the Maintenance Labor by the Maintenance Labor Cost, and then adding the result to the product of the Forecourt Station Labor Requirement and the Forecourt Station Labor Cost.

As mentioned previously, the only energy requirement for a liquid forecourt station is assumed to be electricity for the cryogenic pumps. The other items at a station may also require energy, but it is assumed that the sum of all the other items would be negligible.

Only one liquid pump is assumed to be operating at any given time. Assuming that the pump operates at a 75% adiabatic efficiency, the unit will require approximately 0.33 kWh/kg of hydrogen. This number also includes a small amount of electricity to operate the evaporator fan. To determine the annual energy consumption, 0.33 kg/kWh is multiplied by 365 day/year and the Average Hydrogen Out.

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total utility cost is determined by multiplying either the user-input fuel cost or the H2A value by the Annual Energy Requirement.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.

- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.

- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.

- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.

- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.

- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The value that is calculated in this cell is the annual rent. The value that appears depends on the design capacity of the station. If the user selected a 1,500 kg/day station, then the annual rent cost, based upon H2A Forecourt team calculations, is $28,968/year. If the user selected a 100 kg/day station, then the annual rent is $12,744, again based on H2A Forecourt team calculations.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

6.2.9 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the liquid forecourt station are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

6.3 Compressed Gas H2 Terminal

This tab is used to calculate the contribution to the delivered hydrogen cost for a compressed gas hydrogen terminal. The terminal for hydrogen is envisioned to be similar to a current terminal for gasoline, where the gasoline is stored and then loaded onto trailers for delivery to stations. In the case of hydrogen, the terminal will include compressed gas storage, compressors and equipment for loading the hydrogen into tube trucks. It is assumed that the terminal is served by a pipeline or a central hydrogen production plant. The terminal is assumed to include the following components:

- Gaseous storage
- Storage compressor (to fill the storage system from the pipeline)
- Truck loading compressor(s) (takes the pipeline hydrogen and loads it onto the compressed gas tube trailers).

A simplified process flow diagram of a compressed gas hydrogen terminal is shown in Figure 31.

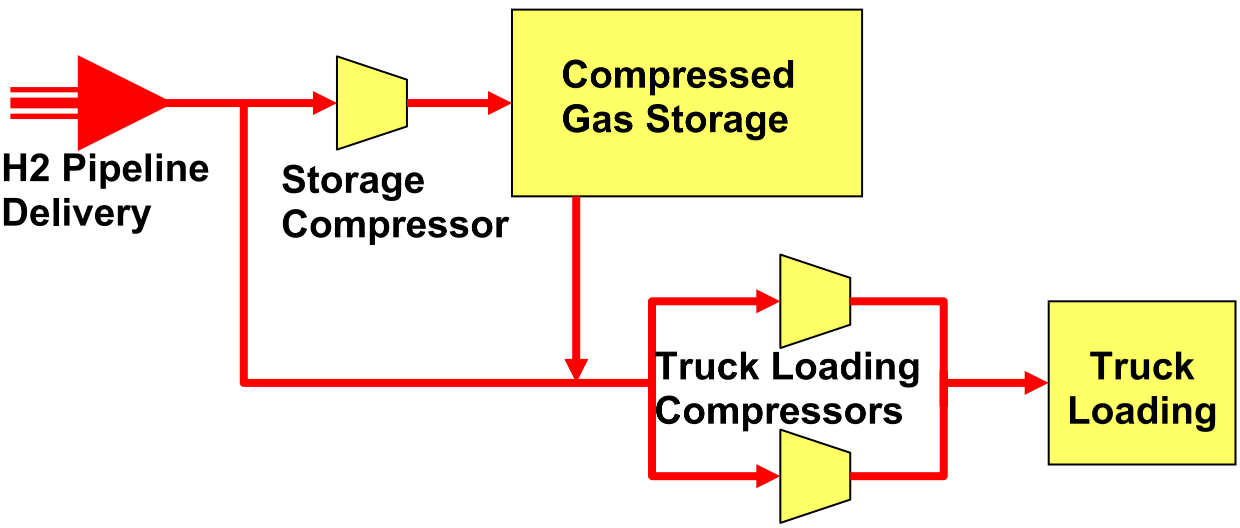

Figure 31. Simplified process flow diagram of a compressed gas hydrogen terminal.

The compressed gas hydrogen terminal tab is basically a combination of the compressor tab and the compressed gas storage tab. Thus, in some areas in this section, the user will be referred to specific sections in the write-up for the other two tabs.

6.3.1 Design Concept

The compressed gas hydrogen terminal tab is designed to cost a combination of gaseous storage, and compressors. The hydrogen is assumed to be delivered to the terminal by a pipeline, or to be co-located with a large central production plant. During normal operation, the hydrogen is taken from either the pipeline or the central plant, and compressed to load onto the tube truck trailers. However, onsite storage is used for times when either the pipeline or central plant might be out of service. A different compressor is used to fill the storage system.

6.3.2 Key Assumptions

- A single compressor is needed to fill the compressed gas storage system (called the Storage Compressor). This compressor is designed to be able to fill the storage in one day.

- The user needs to know either the number of stages in the compressors or the compression ratio per stage. In selecting these values, the user must ensure that typical material temperature constraints are not exceeded, as the model does not check interstage or exit temperatures.

- The theoretical power requirement calculation assumes that the compression work is equally divided between the stages and that an intercooler between each stage brings the gas temperature back to the original inlet temperature.

- It is assumed that there are no pressure drops in the after-cooler or interstage coolers.

- An electrical-powered compressor is assumed. The tab does not allow for the calculation of costs associated with compressors fed with other fuels such as natural gas or hydrogen.

- The only energy expended in running the terminal is for the compressors. The energy use for other ancillary components is assumed to be negligible.

6.3.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Compressed Gas H2 Terminal Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

2. No capital costs are entered.

6.3.4 Design Inputs

The design inputs table is for the user to enter various values that are important for sizing the compressed gas terminal. This table contains a number of yes/no toggle switches, which enhance the flexibility of the model. As this tab includes components that have their tabs, the user may be directed to look at other parts of this manual for information. The items included in this table are described below.

- Average Terminal Demand: Enter the average hydrogen demand from the terminal in kg/day. Please note that this entry is the amount of hydrogen that you actually want to have delivered. The value entered in this cell will be increased in the calculation section if any hydrogen is assumed to be lost during the compression process (hydrogen losses are entered in a later cell).

- Peak Terminal Demand: Enter the peak hydrogen demand from the terminal in kg/day.
- Capacity Factor: The capacity factor is determined by dividing the Average Terminal Demand by the Peak Terminal Demand.
- Pressure of Hydrogen Delivered to the Terminal: The user should enter the pressure of the pipeline or central plant that supplies hydrogen to the terminal.
- Useable Capacity of Individual Tube Trailer: Please enter the capacity of the tube trailer that will be filled at the terminal. This value can be obtained from either of the compressed gas tube trailer tabs.
- Maximum (loading) Pressure in the Tube Trailer: The user needs to enter the maximum pressure of the hydrogen in a tube trailer.
- Maximum Terminal Storage Pressure: Enter the pressure of the onsite hydrogen storage system.
- Number of Days of Storage at the Terminal: Please enter the number of days of backup storage that are available at the terminal. If either the central plant or the pipeline is out of service, this storage will be able to meet the terminal's demand for the number of days entered in this cell.
- The rest of the cells in the Design Inputs table relate to sizing the Storage and Tube Trailer Loading Compressors. Please refer to the Design Inputs table section of the H2 Compressor section in this manual for a description of the inputs.

6.3.5 Scenario Inputs

The entries in this table relate specifically to the set-up of a generic and simple terminal scenario. There are not any yes/no toggle switches, so all cells require input.

- Percentage Per Year That the Storage Compressor is Operated: Since the storage system will not be continuously filled and emptied, the storage compressor will not need to operate constantly. Please enter the amount of time per year that the storage compressor is in operation.
- Time Required to Fill Compressed Gas Tube Trailer: Enter only the time the trailer is attached for filling. The time for maneuvering the trailer at the terminal, and attaching it to the refueling bay, is not included.
- Time Required for Parking, Connection, Disconnection and Removal of Trailer: Enter the time required to hook and unhook the trailer, and the time for moving the trailer around the terminal.

- Width of Individual Bay: This value is used for determining the amount of pipeline required at the terminal. Enter the width of an individual compressed gas tube trailer loading bay.

- Distance from the Storage to the Compressor House: This value is used for determining the amount of pipeline required at the terminal. Please enter the distance from the storage system to the Truck Loading Compressor facility.

- Distance from the Compressor House to the Fill Header: This value is used for determining the amount of pipeline required at the terminal. This distance refers to the length of pipe required to get the hydrogen from the Truck Loading Compressors to the truck fill header.

6.3.6 Calculations

- Maximum Number of Trailer Fills per Day: This value is calculated by dividing the Peak Terminal Demand by the Useable Capacity of an Individual Tube Trailer.

- Number of Filling Bays Required: The following formula is used for this calculation.

$$N_{bays} = \frac{N_{fills}(T_{fill} + T_{park})}{24}$$

Where:

N_{fills} = Maximum Number of Trailer Fills per Day
T_{fill} = Time Required to Fill Compressed Gas Tube Trailer (from the Scenario Table)
T_{park} = Time Required for Parking, Connection, Disconnection and Removal of Trailer (from the Scenarios Table)

- Land Requirement: The total land requirement for the terminal is calculated according to the following assumptions. Each filling bay is approximately 50x70 ft in area. The land for the storage system is determined by raising the ratio of new hydrogen storage capacity to 350 kg (approximate capacity of a Compressed Gas Tube Trailer at 2700 psia maximum pressure) to the 0.8 power. It is assumed that the area of a tube trailer is 180 m^2.

- Length of High Pressure Delivery Header: This value is obtained by multiplying the Width of the Individual Bay by the Number of Filling Bays Required.

- The next three calculations are the same as those in the Design Inputs table of the Compressed Gas H2 Storage Tubes tab. Please reference the section of the manual that describes the compressed hydrogen storage tab.

- Net Hydrogen Delivered: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 days/year.

- The rest of the cells in the Calculation Table are used for calculating the design size of the Truck Loading Compressors and the Storage Compressor. Please see the H2 Compressor tab for specific descriptions of the calculations.

6.3.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section. There are two additional rows in this table, and the entries required are described below.

- Unit Cost of Installed Piping: Please enter the cost of the pipeline required for moving the hydrogen around the compressed gas terminal.

- Cost of Plumbing, Electrical and Instrumentation at Each Individual Bay: Please enter an overall cost for plumbing, electrical and instrumentation for each bay.

6.3.8 Capital Investment

This table is where the capital costs for the specific components in the forecourt station are entered. The user has the option to use the H2A capital costs for the compressors and the compressed gas storage, each of which were described in previous sections.

- Use H2A Compressor Costs?: Please use the toggle switch to enter ***yes*** or ***no***. A description of the cost curve is included in the H2 Compressor section of this manual.

- Use H2A Compressed Gas Storage Costs?: Please use the toggle switch to enter ***yes*** or ***no***. A description of the cost function is included in the Compressed Gas H2 Storage Tubes section of this manual.

If the user selects ***no*** to any of the questions above, then he or she will need to enter their own capital costs.

The rest of the cells in this table are described below.

- Truck Loading Compressor, Number of Compressor Units: This value is linked to the number of compressors required, which was specified in the Design Inputs table.

- Truck Loading Compressor, Power Requirement Per Unit: Please see the H2 Compressor, Capital Investment section for a description of this calculation.

  If the user answered ***yes*** to the question "Use H2A Compressor Cost…", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Storage Compressor, Number of Compressor Units: This value is linked to the number of compressors required, which was specified in the Design Inputs table.

- Storage Compressor, Power Requirement Per Unit: Please see the H2 Compressor, Capital Investment section for a description of this calculation.

If the user answered ***yes*** to the question "Use H2A Compressor Cost…", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Compressed Gas H2 Storage, Size: This value is taken from the Calculations Table.

  If the user answered ***yes*** to the question "Use H2A Compressed Gas Storage Costs?", then no input is required in this row. Otherwise, the user either needs to enter a cost under then "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Piping, Supply, Discharge and Headers: This cost is determined my multiplying the Unit Installed Pipeline Cost from the Economic Parameters table by the sum of the Distance of From Storage to Compressor House, the Distance from the Compressor to the Fill Header, and the Length of the High Pressure Delivery Header.

- Buildings and Structures: The user should either enter a cost for buildings and structures in the "User-Input Installed Cost" column, or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Truck Scale: The user should either enter a cost for a truck scale in the "User-Input Installed Cost" column, or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment.

If ***yes*** was entered for using the H2A Compressor Capital Costs, the entries in this next table will not include the respective costs for the compressors, as the data from the Oil and Gas Journal used for the H2A capital cost curve included all the items included in this table.

- Land Required: This value is fed from the Calculations table.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine the value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Capital Investment: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

6.3.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the terminal are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: Enter the amount of labor-hours per year that are required for operating a compressed gas terminal.

- Labor Cost: Enter the unburdened labor rate for the hours required.

- Total Labor Cost: The total labor cost is determined by the Labor Requirement by the Labor Cost.

The only energy requirement for a compressed gas terminal is assumed to be electricity for the storage and truck loading compressors. The other items at a station may also require energy, but it is assumed that the sum of all the other items would be negligible.

The annual energy requirement for the compressor is different from the theoretical value specified in the Calculations table. During a typical operating year, the feed flowrate to the compressor will fluctuate. Therefore, the average hydrogen flowrate out is used as a basis to calculate the annual energy requirement (see the beginning of this manual for a discussion of peak and average flowrates).

If the user opted to use the idealized power equation, then the following formula is used to determine the annual electricity requirement for either the storage or the truck loading compressor.

$$E_{ann} = 8760 \frac{F_{avg}}{\eta_{isentrop}} ZRT_1 N_{st} \left(\frac{k}{k-1} \right) \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{kN_{st}}} - 1 \right]$$

Where:

$\eta_{isentrop}$ = isentropic compressor efficiency (from Design Inputs table)
F_{avg} = average hydrogen flowrate out, converted to mol/sec (from Design Inputs table)
R = gas constant (specified in the Calculation table)
T_1 = inlet gas temperature, converted to K (from Design Inputs table)
N_{st} = number of compression stages (calculated in the Calculations table)
k = ratio of specific heats (specified as Cp/Cv in the Design Inputs table)
p_2 = outlet pressure (specified in the Design Inputs table)
p_1 = inlet pressure (specified in the Design Inputs table).

For the storage compressor, F_{avg} is not simply the average hydrogen flowrate out. Because the compressor does not operate all the time, and because the compressor needs to be able to fill the storage system in one day, the following calculation is used.

$$F_{avg} = N_{oper} F_{avg,system} T_{storage}$$

Where:

N_{oper} = The Percentage Per Year that the Storage Compressor is Operated (specified in the Scenarios table)
$F_{avg,system}$ = Average Terminal Demand (from the Design Inputs table)
$T_{storage}$ = Number of Days of Storage at Terminal (from the Design Inputs table).

The inlet pressure to the Storage Compressor is always assumed to be the Pressure of the Gas Delivered to the Terminal. However, the outlet pressure will change as the tank is filled. The logarithmic mean of the maximum and minimum pressures in the tank is used for the outlet pressure, p_2. The formula for calculating the logarithmic mean is shown below.

$$p_2 = \frac{p_{\max} - p_{\min}}{\ln\left(\frac{p_{\max}}{p_{\min}}\right)}$$

Where:

p_{max} = maximum storage tank pressure (specified in the Design Inputs table)
p_{min} = minimum storage tank pressure, or the Pressure of the Hydrogen Delivered to the Terminal (specified in the Design Inputs table).

If the user opted to specify a compressor power requirement per kg/hr of hydrogen to size the storage compressor, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 P_{req} \frac{F_{avg}}{24}$$

P_{req} = Power requirement per kg/hr of hydrogen (from Design Inputs table)
F_{avg} = average hydrogen flowrate out for the Storage Compressor. The calculation used for determining this value is shown on the top part of this page.

For the truck loading compressor, F_{avg} is the average hydrogen flowrate out. The inlet pressure to this compressor is always assumed to be the Pressure of the Gas Delivered to the Terminal. However, the outlet pressure will change as the compressed gas tube-trailer is filled. The logarithmic mean of the maximum and minimum pressures in the compressed gas tube-trailer is used for the outlet pressure, p_2. The formula for calculating the logarithmic mean is shown below.

$$p_2 = \frac{p_{\max} - p_{\min}}{\ln\left(\frac{p_{\max}}{p_{\min}}\right)}$$

Where:

p_{max} = maximum pressure in the tube-trailer (specified in the Design Inputs table)
p_{min} = minimum pressure in the tube-trailer (specified in the Design Inputs table).

If the user opted to specify a compressor power requirement per kg/hr of hydrogen to size the truck loading compressor, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 P_{req} \frac{F_{avg}}{24}$$

P_{req} = Power requirement per kg/hr of hydrogen (from Design Inputs table)
F_{avg} = average hydrogen flowrate out (from Design Inputs table).

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total utility cost is determined by multiplying either the user-input fuel cost or the H2A value by the Annual Energy Requirement.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.
- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.
- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.
- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.
- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.
- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.
- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.
- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.
- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.
- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.
- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

6.3.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the compressors are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

6.4 Liquid H2 Terminal

This tab is used to calculate the contribution to the delivered hydrogen cost for a liquid hydrogen terminal. The terminal for hydrogen is envisioned to be similar to a current terminal for gasoline, where the gasoline is stored and then loaded onto trailers for delivery to stations. In the case of hydrogen, the liquid terminal will include liquid hydrogen storage, high pressure cryogenic pumps and equipment for loading the liquid hydrogen onto trucks. It is likely that a liquid hydrogen terminal would be co-located with a liquefier unit. The liquid terminal is assumed to include the following components:

- Liquid hydrogen storage
- Cryogenic pumps (take the liquid hydrogen and loads it onto the LH2 trailers)

A simplified process flow diagram of a liquid hydrogen terminal is shown in Figure 32.

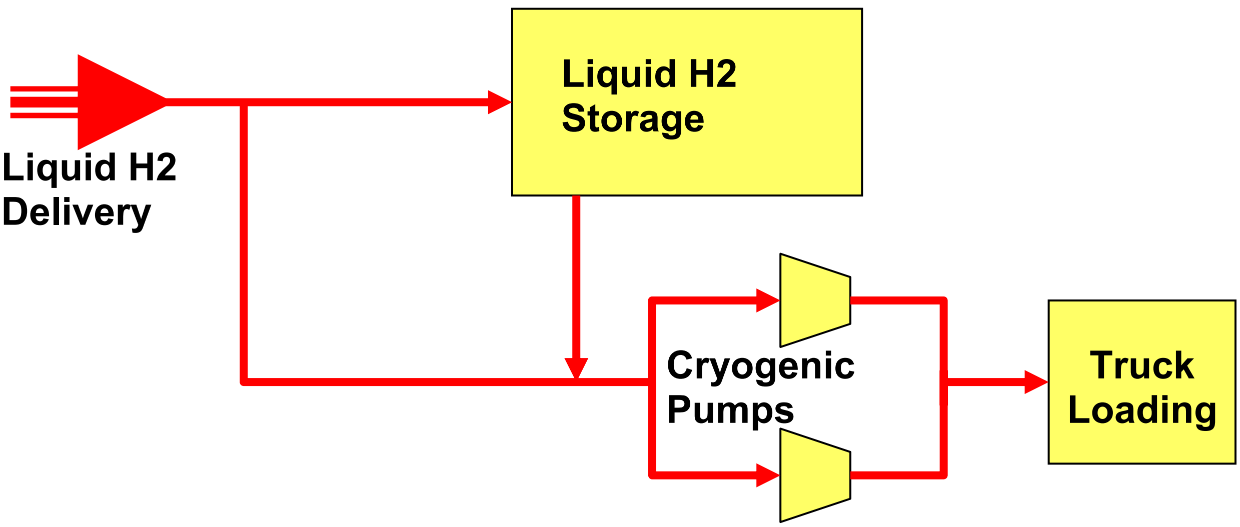

Figure 32. Simplified process flow diagram of a liquid hydrogen terminal.

The liquid hydrogen terminal tab is basically a more complicated version of the Bulk Liquid Hydrogen Storage tab. Thus, in some areas in this section, the user will be referred to specific sections in the write-up for the Bulk Liquid Hydrogen Storage tab.

6.4.1 Design Concept

The liquid hydrogen terminal tab is designed to cost a combination of liquid hydrogen storage, and high pressure cryogenic pumps. The hydrogen is assumed to be delivered to the terminal in liquid form. This assumption implies that the facility would probably be co-located with a liquefier plant. During normal operation, the feed liquid hydrogen is pumped up to pressure, and then loaded onto the liquid hydrogen trailers. However, onsite storage is used for times when the primary source for liquid hydrogen is inoperable.

6.4.2 Key Assumptions

- Each of two pumps is designed to handle 75% of the peak flowrate.

- The storage at the facility is only used when the primary feed source is off-line.
- There is no energy required to operate the liquid terminal facility. The energy use for all components, including the liquid pumps, is assumed to be negligible.

6.4.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Liquid H2 Terminal Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.
2. No capital costs are entered.

6.4.4 Design Inputs

The design inputs table is used for entering values to determine how much hydrogen will be processed by the facility, and how much onsite liquid hydrogen storage is required.

- Average Terminal Demand: Enter the average hydrogen demand from the terminal in kg/day. Please note that this entry is the amount of hydrogen that you actually want to have delivered from the terminal. The value entered in this cell will be increased in the calculation section if any hydrogen is assumed to be lost during the terminal transfer, loading or storing processes (hydrogen losses are entered in a later cell).
- Peak Terminal Demand: Enter the peak hydrogen demand from the terminal in kg/day. .
- Capacity Factor: The capacity factor is determined by dividing the Average Terminal Demand by the Peak Terminal Demand.
- Useable Percent of Liquid Storage Unit (%): The user needs to enter a percentage of total liquid hydrogen storage capacity that is useable. Remember that a certain percentage of the liquid hydrogen stored should remain in the storage vessel to keep the internal parts cold, therefore eliminating boil-off concerns during charging.
- Boil-off Rate: During storage, a portion of the liquid hydrogen will boil-off and be vented through a relief value on the vessel. This value should be entered as a percentage loss per day, based on the total volume of the storage system.

6.4.5 Scenario Inputs

The entries in this table relate specifically to the set-up of a generic and simple terminal scenario. There are no yes/no toggle switches, so all cells require input.

- Time Required per Fill: Enter only the time the liquid hydrogen trailer is attached for filling. The time for maneuvering the trailer at the terminal, and attaching it to the refueling bay, is not included.

- Time Required for Parking, Connection, Disconnection and Removal of Trailer: Enter the time required to hook and unhook the liquid hydrogen trailer, and the time for moving the trailer around the terminal.

- Number of Days of Storage: This input is multiplied by the average hydrogen demand to determine the size of the desired liquid hydrogen storage system.

- Width of Individual Bay: This value is used for determining the amount of pipeline required at the terminal. Enter the width of an individual loading bay.

- Distance from the Storage to the Pump: This value is used for determining the amount of pipeline required at the terminal. Please enter the distance from the storage system to the high temperature cryogenic pumps.

- Distance from the Pump to the Fill Header: This value is used for determining the amount of pipeline required at the terminal. This distance refers to the length of pipe required to get the hydrogen from the cryogenic pumps to the truck fill header.

6.4.6 Calculations

- Capacity of Individual Liquid Hydrogen Trailer: This cell is linked to the Truck-LH2 Delivery tab, and reads the calculated capacity of an individual LH2 trailer.

- Maximum Number of Trailer Fills per Day: This value is calculated by dividing the Peak Terminal Demand by the capacity of the liquid hydrogen trailer.

- Number of Filling Bays Required: The following formula is used for this calculation.

$$N_{bays} = \frac{N_{fills}(T_{fill} + T_{park})}{24}$$

Where:

N_{fills} = Maximum Number of Trailer Fills per Day
T_{fill} = Time Required to Fill, connected time (from the Scenario Table)
T_{park} = Time Required for Parking, Connection, Disconnection and Removal of Trailer (from the Scenarios Table)

- Peak LH2 Pump Capacity: The liquid hydrogen pump capacity is calculated using the following formula.

$$Cap_{pump} = F_{peak}\left(1 + \frac{T_{park}}{T_{fill}}\right)$$

Where:

F_{peak} = Peak Terminal Demand (from the Design Inputs table)
T_{park} = Time for Parking, Connection, Disconnection and Removal of the Trailer (from the Scenario Inputs table)
T_{fill} = Time Required per Fill, Connected Time (from the Scenario Inputs table)

- Number of LH2 Pumps Required: Two pumps, each designed at 75% of the Peak LH2 Pump Capacity, are used.

- Design Capacity of Each LH2 Pump: The Peak LH2 Pump Capacity is multiplied by 0.75 to get the design capacity for each pump.

- The next three cells are used for sizing the liquid hydrogen storage tank(s). Please see the Bulk Liquid Hydrogen Storage tab, Calculations section, for a description of the calculations.

- Land Requirement: The total land requirement for the terminal is calculated according to the following assumptions. Each filling bay is approximately 50x70 ft in area. The space required for the liquid storage tanks is calculated using the same correlations as presented in the Bulk Hydrogen Liquid Storage tab.

- Length of High Pressure Delivery Header: This value is obtained by multiplying the Width of the Individual Bay by the Number of Filling Bays Required.

- Net Hydrogen Delivered: This value is calculated by multiplying the Average Hydrogen Flowrate Out by 365 days/year.

6.4.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section. There are two additional rows in this table, and the entries required are described below.

- Unit Cost of Installed Piping: Please enter the cost of the pipeline required for moving the hydrogen around the compressed gas terminal.

- Cost of Plumbing, Electrical and Instrumentation at Each Individual Bay: Please enter an overall cost for plumbing, electrical and instrumentation for each bay.

6.4.8 Capital Investment

This table is where the capital costs for the specific components in the liquid hydrogen terminal are entered.

- Use H2A Liquid Storage Costs?: Please use the toggle switch to enter ***yes*** or ***no***. A description of the cost curve is included in the Bulk Liquid Hydrogen Storage section of this manual.

- Use H2A Liquid Pump Costs?: Please use the toggle switch to enter ***yes*** or ***no***. The value used is based on a vendor quotation for a high pressure pump. It is assumed that the pump cost for this application is 1/2 of the cost of the high pressure pump. Thus, the pump cost is assumed to be $150/kg/hr of hydrogen throughput.

If the user selects ***no*** to any of the questions above, then he or she will need to enter their own capital costs.

The rest of the cells in this table are described below.

- Liquid Storage Capacity: This value is taken from the Design Inputs table.

- Liquid Storage Cost: If the user answered ***yes*** to the question "Use H2A Liquid Storage Costs", then no input is required in this row. Otherwise, the user either needs to enter a cost under the "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- LH2 Pump, Number of Units: This number was specified in the Calculations table.

- LH2 Pump Capacity Per Unit: This number was specified in the Calculations table.

- LH2 Pump Cost, per Unit: If the user answered ***yes*** to the question "Use H2A Liquid Pump Costs", then no input is required in this row. Otherwise, the user either needs to enter a cost under the "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns. If manually entering the pump cost, remember that the values entered should be on a per unit basis.

- Piping, Supply, Discharge and Headers: This cost is determined my multiplying the Unit Installed Pipeline Cost from the Economic Parameters table by the sum of the Distance From the Storage to the Pump House, the Distance from the Pump House to the Fill Header, and the Length of the Delivery Header.

- Buildings and Structures: The user should either enter a cost for buildings and structures in the "User-Input Installed Cost" column, or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Truck Scale: The user should either enter a cost for a truck scale in the "User-Input Installed Cost" column, or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment.

- Land Required: This value is fed from the Calculations table.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The land cost is multiplied by the land required to determine value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Capital Investment: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

6.4.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the liquid hydrogen terminal are entered. The table is divided into two sections: labor and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: Enter the amount of labor-hours per year that are required for operating a liquid terminal.
- Labor Cost: Enter the unburdened labor rate for the hours required.
- Total Labor Cost: The total labor cost is determined by the Labor Requirement by the Labor Cost.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.
- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.
- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.
- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.
- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.
- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.
- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.
- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.
- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.
- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.
- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

6.4.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the compressors are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

6.5 Gaseous H2 Geologic Storage

This tab is used to calculate the contribution to the delivered hydrogen cost for a gaseous hydrogen geologic storage system. Similar systems are used in the natural gas infrastructure. In essence, the hydrogen would be stored in some type of underground aquifer or salt dome. A geologic storage system would typically be installed along side a pipeline, and its primary purpose would be storing hydrogen for times when there are demand surges. The components required for a geologic gas storage system include a compressor (for charging and discharging the cavern) and some type of underground cavern.

A simplified process flow diagram of a gaseous geologic storage system is shown in Figure 33 on the next page.

The compressed gas hydrogen terminal tab is basically a more complex version of the H2 Compressor tab. Thus, in some areas in this section, the user will be referred to specific sections in the H2 Compressor tab.

The information used to design this tab was adapted from several different sources (Duke Energy, 2005; US EPA, 2003; Natural Resources Canada,)

6.5.1 Design Concept

The gaseous geologic storage system is used to provide excess hydrogen to a pipeline system when there is a surge in demand. The cavern is assumed to be filled during times when the capacity is lower than the average daily demand (perhaps in the Winter months when people are not driving as often as they are in the summer). The cavern in this model is designed assuming that it is charged during the off-peak time of the year, and then discharged during the peak usage period. There is only one filling cycle each year.

The compressor can both charge the cavern and discharge the cavern. Because a pipeline is assumed to feed the hydrogen to the cavern, the compressor will only be needed to charge the geologic storage system when the pressure in the cavern is greater than the pipeline pressure. Likewise, the compressor will only be used during the discharging process when the cavern pressure is less than the pipeline pressure.

6.5.2 Key Assumptions

- The cavern is filled once, and discharged once, during the year. The filling process occurs during off-peak period, and the discharging process occurs during the surge period.
- A single compressor system is used to fill and empty the geologic storage system. There is not a set of compressors for filling the system, and then another set for discharging the system.
- The user needs to know either the number of stages in the compressors or the compression ratio per stage. In selecting these values, the user must ensure that typical

material temperature constraints are not exceeded, as the model does not check interstage or exit temperatures.

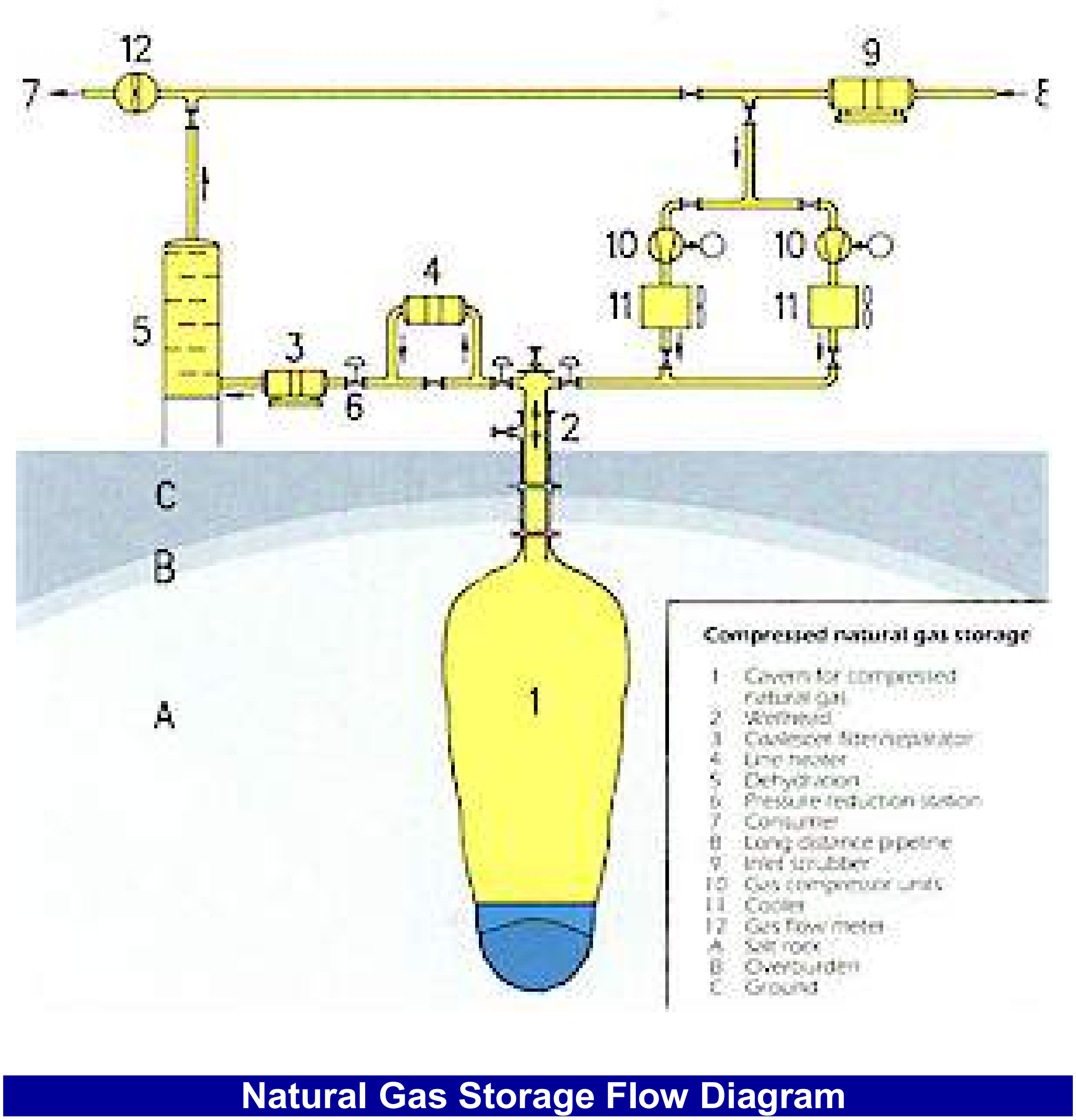

Figure 33. Process Flow Diagram of a Gaseous Hydrogen Geologic Storage System

- The theoretical power requirement calculation assumes that the compression work is equally divided between the stages and that an intercooler between each stage brings the gas temperature back to the original inlet temperature.

- It is assumed that there are no pressure drops in the after-cooler or interstage coolers.

- An electrical-powered compressor is assumed. The tab does not allow for the calculation of costs associated with compressors fed with other fuels such as natural gas or hydrogen.

- The only energy expended in running the terminal is for the compressors. The energy use for other ancillary components is assumed to be negligible.

- The cavern is sized such that it can supply a certain period of surge without having to be refilled.

- The cavern cannot be discharged at the same rate that it is filled. The H2A delivery team assumes that maximum injection rate is 66% of the withdrawal rate. This assumption is based on natural gas cavern operating experience.

6.5.3 Error Messages

The error messages will appear in the rows between the Calculation Outputs table and the Gaseous Geologic Storage Design Inputs table. If no errors are detected in the data that has been entered, the user will see the following message in green, capital letters below the Calculation Outputs table.

THERE ARE NO ERRORS PRESENT ON THIS SHEET.

Error messages, which will appear in red letters, have been programmed for the following items:

1. A cell with a required entry is left blank. The error message will direct the user to the table where the error has occurred.

2. No capital costs are entered.

3. The total days for filling the cavern added to the total days for discharging the cavern sums to greater than 365 days. Remember that the cavern is designed to operate under one fill/empty cycle per year.

6.5.4 Design Inputs

The design inputs table is for the user to enter various values that are important for sizing the gaseous H2 geologic storage system. This table contains a number of yes/no toggle switches, which enhance the flexibility of the model. As this tab includes components that have their own tabs, the user may be directed to look at other parts of this manual for information. The items included in this table are described below.

- Average System Demand: Enter the average system demand for the pipeline on which the geologic storage system is located. This value should correspond to the average daily flowrate in the pipeline.

- Cavern Maximum Pressure: The user needs to enter the maximum pressure of hydrogen that can be stored in the geologic storage system.

- Cavern Minimum Pressure: Enter the pressure when the geologic storage system is considered empty. This value will probably not be atmospheric pressure, as a certain amount of gas will need to be left in the cavern even when it's considered "empty".

- Cavern Temperature: Enter the temperature of the hydrogen when stored in the underground cavern.

- Pipeline Pressure of Hydrogen in Feeder to the Cavern: Enter the pressure of the hydrogen in the pipeline that is used in conjunction with the cavern.

- Inlet Hydrogen Temperature to the Compressor: Enter the temperature of the hydrogen when it enters the compressor.

- The rest of the cells in the Design Inputs table relate to sizing the compressor. Please refer to the Design Inputs table section of the H2 Compressor section in this manual for a description of the inputs.

6.5.5 Scenario Inputs

The entries in this table relate specifically to the set-up of a generic and simple geologic storage system. There are no yes/no toggle switches, so all cells require input.

- Surge: % Above the Average Demand: Please enter the percent above the Average System Demand for the Surge period. This percentage relates to the amount of hydrogen that the geologic storage system will supply to the hydrogen pipeline.

- Number of Days of Surge: Enter the days that the surge, specified in the previous cell, lasts.

- Maximum Allowable Daily Hydrogen Withdrawal Rate: Enter the maximum daily withdrawal rate as a percentage of total cavern capacity.

- Maximum Allowable Injection Rate: Enter the maximum allowable injection rate, as a percentage of the withdrawal rate. Remember that the injection rate will always be less than the withdrawal rate.

6.5.6 Calculations

- Mean Compressibility Factor: A detailed description of the compressibility factor calculations is described in the General Comments section of the manual.

- Design Cavern Useable Capacity at Maximum Pressure: This value is calculated with the following formula.

  $$C_{cav} = F_{avg} Surge T_{surge}$$

  Where:

  F_{avg} = Average System Demand (from Design Inputs table)
  $Surge$ = Surge: % Above the Average Demand (from the Scenario Inputs table)

T_{surge} = Number of Days of Surge (from the Scenario Inputs table).

- The next two cells calculate the actual size of the cavern. Please see the Compressed Gas H2 Storage Tubes, Calculation table section, part of this manual for a detailed description.

- Resizing Cavern Because Maximum Withdrawal…: The message will only appear if required withdrawal rate is greater than the maximum withdrawal rate, as specified previously. A message will show to the right of the Calculation table to alert the user whether or not the cavern was resized.

- Resized Design Cavern Capacity: A value will only appear in this cell if the message in the previous cell also is shown. The following formula is used to recalculate the new cavern capacity, if the required withdrawal rate is greater than the maximum withdrawal rate.

  $$C_{cav,new} = \frac{F_{avg} Surge}{F_{\max} C_{cav}}$$

  Where F_{avg} and *Surge* are defined previously, and:

  Fmax = Maximum Allowable Daily Hydrogen Withdrawal Rate (from the Design Scenarios tab)
  C_{cav} = Calculated Useable Cavern Capacity.

- Design Cavern Capacity: The volume of the geologic storage cavern is calculated in this cell. If the Resized Design Cavern Capacity is used, then that value is multiplied by 11.126 Nm^3/kg of hydrogen to give the capacity in Nm^3 of hydrogen. Otherwise, the Design Cavern capacity is multiplied by the same factor to give the desired result.

- Design Cavern Water Volume: The water volume of the geologic storage cavern is calculated in this cell. The result of the calculation used in this cell is for informational purposes only. The volume is calculated according to the following equation.

  $$V = \frac{C_{des} Z T_{oper} R}{P_{\max}}$$

  Where:

  C_{des} = Resized Design Cavern Capacity, or Design Cavern Capacity, converted to moles of hydrogen
  Z = compressibility factor
  T_{oper} = Cavern Temperature, converted to K (from Design Inputs table)
  R = gas constant, 8.2x10-5 psi/mol.K
  P_{max} = Cavern Maximum Pressure (from Design Inputs table)

- Actual Base (Cushion) Gas Capacity: The cushion gas refers the hydrogen that remains in the cavern when it is considered empty. Since this gas is never used, it has to be paid for during the initial charge of the cavern. The equation used to calculate this number is defined as follows.

  $$C_{cushion} = \left(\frac{C_{des} - C_{use}}{C_{des}} \right)$$

  Where:

  C_{des} = Resized Design Cavern Capacity, or Design Cavern Capacity, converted to moles of hydrogen
  C_{use} = Design Cavern Useable Capacity at Maximum Pressure.

- Base (Cushion) Gas: This value is determined by subtracting the Design Cavern Useable Capacity from either the Resized Design Cavern Capacity or the Design Cavern Capacity.

- Time to Discharge Cavern from Maximum to Minimum Pressure: This value is equivalent to the Number of Days of Surge.

- Time to Charge Cavern from Minimum to Maximum Pressure: This value is calculated by dividing the Time to Discharge Cavern from Maximum to Minimum Pressure by the the Maximum Allowable Injection Rate.

- Net Hydrogen Delivered: This value is the same as the Design Cavern Useable Capacity at Maximum Pressure

- Peak Compressor Withdrawal Mass Rate: This value corresponds to the compressor withdrawal rate during the peak part of the year. The formula used depends on whether the Resized Design Cavern Capacity was activated.

  In the case that the Resized Design Cavern Capacity cells are active, then the following formula is used.

  $$F_{comp,peak} = \frac{W_{rate} C_{des}}{1 - loss}$$

  Where:

  W_{rate} = Maximum Daily Allowable Withdrawal Rate (from Scenario table)
  C_{des} = Resized Design Cavern Capacity
  $loss$ = Hydrogen Loss During Compression (from Design Inputs table)

  If the Resized Design Cavern Capacity cells are not active, then the following formula is used.

$$F_{comp,peak} = \frac{F_{avg} Surge}{1 - loss}$$

Where all variables have been defined previously.

- Peak Compressor Withdrawal Volume Rate: This value is obtained by multiplying the Peak Compressor Withdrawal Mass Rate by 11.126 Nm^3/kg of Hydrogen.

- Peak Compressor Injection Volume Rate: To obtain this number, the Peak Compressor Withdrawal Volume Rate is multiplied by the Maximum Allowable Injection Rate (which was specified in the Scenarios table).

- The next five cells Calculation Table are used for calculating the design size of the Geologic Storage compressor. Please see the H2 Compressor tab for specific descriptions of the calculations.

- Time to Discharge Cavern to Pipeline Pressure: The result shown in this cell is used to determine when the compressor is actually operating. The following equation is used to determine this number.

$$T_{pipe,dis} = \frac{V}{ZRT_{oper}} \left(\frac{2(P_{max} - P_{pipe})}{F_{avg} Surge} \right)$$

Where all variables have been defined previously except:

P_{pipe} = Pipeline Pressure of Hydrogen in Feeder to the Cavern (from the Design Inputs table).

- Time to Charge Cavern to Pipeline Pressure: The result shown in this cell is used to determine when the compressor is actually operating. The following equation is used to determine this number.

$$T_{pipe,charge} = \frac{V}{ZRT_{oper}} \left(\frac{2(P_{pipe} - P_{min})}{I_{rate} F_{avg} Surge} \right)$$

Where all variables have been defined previously except:

P_{min} = Cavern Minimum Pressure (from the Design Inputs table)
I_{rate} = Maximum Allowable Injection Rate (from the Scenario table).

6.5.7 Economic Assumptions

The specific inputs for this table are described in the Financial Analysis section. There is a single additional row in this table, and the entry required is described below.

- Hydrogen Cost for Base Gas: Please enter the cost of the hydrogen gas that will serve as the base gas (i.e. remain in the cavern when empty, as the cavern can never be fully emptied).

6.5.8 Capital Investment

This table is where the capital costs for the specific components in the geologic cavern are entered. The user has the option to use the H2A capital costs for the cavern, compressor and other equipment required for operation of the geologic storage system.

- Use H2A Costs for the Cavern/Well…?: Please use the toggle switch to enter ***yes*** or ***no***. The cost correlation is shown below. The final result is inflated to Year 2005 dollars using standard H2A inflation factor of 1.9%/year.

$$Cost_{cav} = 3{,}156{,}000\left(\frac{V}{19{,}000{,}000}\right)^{0.7}$$

  Where:

  V = Design Cavern Water Volume (calculated in the Calculations table).

- Use H2A Costs for Other Equipment in Geologic Storage Systems…?: Please use the toggle switch to enter ***yes*** or ***no***. The cost correlation is shown below. Other equipment includes dryers and storage at the site. The final result is inflated to Year 2005 dollars using standard H2A inflation factor of 1.9%/year.

$$Cost_{other} = 1{,}609{,}406\left(\frac{I_{rate}}{875{,}000}\right)^{0.7}$$

  Where:

  I_{rate} = Peak Compressor Injection Volume Rate (calculated in the Calculations table).

- Use H2A Compressor Costs…?: Please use the toggle switch to enter ***yes*** or ***no***. A description of the cost curve is included in the H2 Compressor section of this manual.

If the user selects ***no*** to any of the questions above, then he or she will need to enter their own capital costs.

The rest of the cells in this table are described below.

- Base Gas: The value that shows in the Calculated Installed Cost is determined by multiplying the Hydrogen Cost for Base Gas (from Economic Inputs table) by the Base (Cushion) Gas requirement which is calculated in the Calculations Table.

- Cavern/Well Useable Capacity: This value is taken from the Calculations table.

  If the user answered ***yes*** to the question "Use H2A Costs for Cavern/Well…", then no input is required in this row. Otherwise, the user either needs to enter a cost under the "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Compressor, Number of Units: The value shown is linked to the number of compressors required, which was specified in the Design Inputs table.

- Compressor, Power Requirement Per Unit: Please see the H2 Compressor, Capital Investment section for a description of this calculation.

  If the user answered ***yes*** to the question "Use H2A Compressor Cost…", then no input is required in this row. Otherwise, the user either needs to enter a cost under the "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Injection Rate: This value was calculated in the Calculations table.

  If the user answered ***yes*** to the question "Use H2A Costs for Other Equipment…", then no input is required in this row. Otherwise, the user either needs to enter a cost under the "User-Input Installed Cost", or enter a cost in the "User-Input Uninstalled Cost" and the "Installation Cost Factor" columns.

- Balance of Component: This item includes any other equipment that might be required for operation of a compressed gas forecourt station that has not already been included in the previous items.

The table immediately below the Capital Cost table is for entering land costs, as well as some direct and indirect capital costs. The values entered in this table allow the determination of a total capital investment.

If ***yes*** was entered for using the H2A Compressor Capital Costs, the entries in this next table will not include the respective costs for the compressors, as the data from the Oil and Gas Journal used for the H2A capital cost curve included all the items included in this table.

- Use H2A Correlation for Land Cost to Determine Total Land Cost?: Please use the toggle switch to answer ***yes*** or ***no***. The H2A land cost for geologic storage is based upon data extrapolated from the Saltville Salt Cavern project (Duke Energy, 2005). The cost correlation is shown below. The final result is inflated to Year 2005 dollars using the standard H2A inflation factor of 1.9%/year.

  $$Land_{cav} = 339{,}543\left(\frac{C_{use}}{232{,}000}\right)^{0.6}$$

  Where:

  C_{use} = Design Cavern Useable Capacity at Maximum Pressure (calculated in the Calculations table).

If ***yes*** was selected, then no input is required in the following two cells.

- Land Required: Please enter the land required for the geologic storage cavern.

- Land Cost: The cost, per m^2, of the land specified in the above cell should be entered.

- Total Land Cost: The value that shows up in this cell depends on the response to the questions "Use H2A Correlation for Land Cost to Determine Total Land Cost?" If the user entered ***yes***, then the value shown in this cell is the result of the land cost correlations. Otherwise, the land cost is multiplied by the land required to determine value in this cell.

- Site Preparation: Any costs associated with the preparation of the site should be included in this value, which is entered as a percentage of the Total Initial Capital Investment.

- Site Preparation Cost: The Site Preparation percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Engineering and Design: Enter, as a percentage of Total Initial Capital Investment, the cost of engineering and design.

- Engineering and Design Cost: The Engineering and Design percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Project Contingency: Enter the percentage of the Total Initial Capital Investment that should be added for project contingency. Project Contingency typically accounts for any unexpected costs which always come up during a project.

- Project Contingency Cost: The Project Contingency percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- One Time Licensing Fees: Please enter the percentage of the Total Initial Capital Investment that should be allocated to pay for one time licensing fees.

- One Time Licensing Fees Cost: The One Time Licensing Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Up-Front Permitting Fees: The user should enter the fees that may be associated with permitting of the process, as a percentage of the Total Initial Capital Investment, in this cell.

- Up-Front Permitting Fees Cost: The Up-Front Permitting Fees percentage entered in the previous cell is multiplied by the Total Initial Capital Investment to obtain this value.

- Other Capital: Any other capital costs, whether direct or indirect, should be entered into this cell as a dollar value.

- Total Land/Other Capital Costs: The costs determined in this table for land and other capital, are summed and the result is shown in this cell.

- Total Capital Investment: The Total Land/Other Capital Costs is summed with the Total Initial Capital Investment to determine this number.

6.5.9 Operating and Maintenance Costs

In this table, the annual costs required for operating the geologic storage system are entered. The table is divided into three sections: labor, fuel/utilities, and the remainder of costs. This table includes a combination of user required entries and calculations. It is important to remember the color-coding when entering values.

In the labor section, the following items are included:

- Labor Requirement: Enter the amount of labor-hours per year that are required for operating a compressed gas terminal.
- Labor Cost: Enter the unburdened labor rate for the hours required.
- Percent Allocated to Compressor: Please enter the percentage of the total labor requirement that should be allocated to the compressor.
- Total Labor Cost: The total labor cost is determined by multiplying the Labor Requirement by the Labor Cost.

The only energy requirement for a geologic storage system is assumed to be electricity for the compressor(s). Other items may also require energy, but it is assumed that the sum of all the other items would be negligible.

The annual energy requirement for the compressor is different from the theoretical value specified in the Calculations table. The compressor will only be operating in the following two scenarios.

1. The cavern is being discharged, and the pressure in the cavern is less than the pipeline pressure.
2. The cavern is being charged, and the pressure in the cavern is greater than the pipeline pressure.

During a typical operating year, the feed flowrate to the compressor will fluctuate. Therefore, the average hydrogen flowrate out is used as a basis to calculate the annual energy requirement (see the beginning of this manual for a discussion of peak and average flowrates).

If the user opted to use the idealized power equation, then the following formula is used to determine the annual electricity requirement for the compressor. Note that the equation includes two parts. The first corresponds to scenario 1 (described above), and the second corresponds to scenario 2 (described above).

$$E_{ann} = 8760 Surge \frac{F_{avg}}{\eta_{isentrop}} ZRT_1 N_{st} \left(\frac{T_{dis,\max mim} - T_{pipe,dis}}{365} \right) \left(\frac{k}{k-1} \right) \left[\left(\frac{p_{2,dis}}{p_{1,dis}} \right)^{\frac{k-1}{kN_{st}}} - 1 \right] +$$

$$8760 Surge I_{rate} \frac{F_{avg}}{\eta_{isentrop}} ZRT_1 N_{st} \left(\frac{T_{ch\arg e,\max mim} - T_{pipe,ch\arg e}}{365} \right) \left(\frac{k}{k-1} \right) \left[\left(\frac{p_{2,ch\arg e}}{p_{1,ch\arg e}} \right)^{\frac{k-1}{kN_{st}}} - 1 \right]$$

Where:

$\eta_{isentrop}$ = isentropic compressor efficiency (from Design Inputs table)
Surge = Surge: % Above the Average Demand (from the Scenario Inputs table)
F_{avg} = average hydrogen flowrate out, converted to mol/sec (from Design Inputs table)
R = gas constant (specified in the Calculation table)
T_1 = inlet gas temperature, converted to K (from Design Inputs table)
N_{st} = number of compression stages (calculated in the Calculations table)
$T_{dis,maxmin}$ = Time to Discharge Cavern from Maximum to Minimum Pressure (calculated in the Calculations Table)
$T_{pipe,dis}$ = Time to Discharge Cavern to Pipeline Pressure (calculated in the Calculations Table)
k = ratio of specific heats (specified as Cp/Cv in the Design Inputs table)
p_{pipe} = Pipeline Pressure in Feeder to Cavern (specified in the Design Inputs table)
$p_{1,dis}$ = Cavern Minimum Pressure, calculated as a logarithmic mean (see below)
I_{rate} = Maximum Allowable Injection Rate (from the Scenarios table)
$T_{charge,maxmin}$ = *Time to Charge Cavern from Maximum to Minimum Pressure*(calculated in the Calculations Table)
$T_{pipe,charge}$ = *Time to Charge Cavern to Pipeline Pressure* (calculated in the Calculations Table)
$p_{2,charge}$ = Cavern Maximum Pressure, calculated as a logarithmic mean (see below)

The pressure in the cavern will change as it is either emptied or filled. Therefore, the logarithmic mean of the pipeline pressure and the minimum cavern pressure is used when the cavern is being discharged (first part of the energy equation). The formula for calculating the logarithmic mean is shown below.

$$p_{1,dis} = \frac{p_{pipe} - p_{\min}}{\ln\left(\frac{p_{pipe}}{p_{\min}} \right)}$$

Where p_{pipe} has already been specified and:

p_{min} = Cavern Minimum Pressure (specified in the Design Inputs table).

The logarithmic mean of the maximum cavern pressure and the pipeline pressure is used when the cavern is being charged (second part of the energy equation). The formula for calculating the logarithmic mean is shown below.

$$p_{2,charge} = \frac{p_{max} - p_{pipe}}{\ln\left(\frac{p_{max}}{p_{pipe}}\right)}$$

Where p_{pipe} has already been specified and:

P_{max} = Cavern Maximum Pressure (specified in the Design Inputs table).

If the user opted to specify a compressor power requirement per kg/hr of hydrogen, then the following formula is used to determine the annual electricity requirement.

$$E_{ann} = 8760 Surge P_{req} F_{avg}((T_{dis,\max mim} - T_{pipe,dis}) + (T_{charge,\max mim} - T_{pipe,charge}))$$

Where all variables have already been defined, except:

P_{req} = Compressor Power Required (from the Design Inputs table).

As described in a previous section, the user can either enter their cost of fuel/utility or to select the fuel/utility cost from the H2A feedstock tab. The total utility cost is determined by multiplying either the user-input fuel cost or the H2A value by the Annual Energy Requirement.

The remainder of the cells in the Operation and Maintenance table are described below:

- Insurance: This entry handles all insurance that is required by the operator. The value needs to be entered on a percentage of Total Capital Investment.
- Insurance Cost, annual: The annual insurance cost is determined by multiplying the insurance percentage specified previously by the Total Capital Investment.
- Property Taxes: A percentage of the Total Capital Investment should be allocated for annual property taxes.
- Property Taxes, annual: The annual property taxes are calculated by multiplying the Total Capital Investment by the property tax rate previously described.
- Licensing and Permits: The licensing and permits O&M cost needs to be entered as a percentage of Total Capital Investment. The entry should include all licensing and permit fees for operating the compressor.
- Licensing and Permits, annual: The annual insurance cost is determined by multiplying the licensing cost percentage by the Total Capital Investment.

- Operating, Maintenance and Repairs: As a percentage of the Total Capital Investment, the user needs to enter the cost for annual operating maintenance and repair items.

- Operating, Maintenance and Repairs, annual: The annual operating, maintenance and repair cost is determined by multiplying the Operating, Maintenance and Repairs percentage by the Total Capital Investment.

- Overhead and G&A: These costs are determined based on a percentage of the total labor cost. When entering this percentage, the user needs to remember that the labor costs are unloaded.

- Overhead and G&A: The annual overhead and G&A expense is determined by multiplying the total labor cost by the percentage previously described.

- Other Fixed Operating Costs: The user should enter any other potential operating costs that are not covered by previous items in this cell.

The annual amounts for each item in the Operating and Maintenance table are summed together at the bottom table.

6.5.10 Cost Calculations

The detailed financial calculations are discussed in a previous section.

The capital, labor, fuel and other O&M costs for the compressor and cavern are pooled together so that the hydrogen cost can be determined. The results from the calculation are fed to the table at the top of the tab, where the total hydrogen cost, as well as contributions to that cost, is shown.

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