

SPE 54107

## Successful Pilot of Thermosyphon Process Heater Reduces GHG Emissions and Operating Costs

W.A. Arnold, SPE, PanCanadian Resources, and J.I. Neulander, Hudson Products Corporation

Copyright 1999, Society of Petroleum Engineers Inc.

This paper was prepared for presentation at the 1999 SPE International Thermal Operations and Heavy Oil Symposium held in Bakersfield, California, 17–19 March 1999.

This paper was selected for presentation by an SPE Program Committee following review of information contained in an abstract submitted by the author(s). Contents of the paper, as presented, have not been reviewed by the Society of Petroleum Engineers and are subject to correction by the author(s). The material, as presented, does not necessarily reflect any position of the Society of Petroleum Engineers, its officers, or members. Papers presented at SPE meetings are subject to publication review by Editorial Committees of the Society of Petroleum Engineers. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of the Society of Petroleum Engineers is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of where and by whom the paper was presented. Write Librarian, SPE, P.O. Box 833836, Richardson, TX 75083-3836, U.S.A., fax 01-972-952-9435.

### Abstract

PanCanadian originally pursued thermosyphon technology to lower operating costs. However, it is now apparent that a more significant benefit is reduction of greenhouse gas (GHG) emissions. Other benefits include loss management, increased safety, improved operability and maintenance cost reduction.

A prototype Thermflo™ thermosyphon process heater was developed by Hudson Products Corporation (HPC) as a joint effort with PanCanadian Petroleum Ltd. The unit was installed in a 320 m<sup>3</sup> atmospheric heavy oil tank in northeastern Alberta in November '97. Performance testing was carried out over the next several months and evaluated using API Standards & Recommended Practices.

The testing was carried out in two phases. In phase one, we compared the performance of the thermosyphon to a naturally drafted venturi style nozzle burner in a firetube located in an adjacent tank. Both units were fired using sales utility gas. Increased combustion efficiency and improved heat transfer reduced fuel gas consumption by 33% and cut GHG emissions by 40%. In phase two of the testing, the prototype successfully burned solution gas normally vented to atmosphere. This translates to an annual operating cost saving of about \$40,000 and GHG emission reduction of about 10,000 tonnes per year.

### Introduction

The thermosyphon process heater is a means of transferring heat from an external combustion chamber to liquid inside a

process vessel or tank. It does this without having a flame within a firetube inside the vessel or tank and is therefore, significantly more efficient and safer than a firetube. Employment of a prototype heater in a heavy oil field production tank pilot project confirmed the concept and the improved efficiency lead to substantial reduction in GHG emission, lower operating costs and improved safety.

### Background

**Production Methodology.** The preferred strategy of cold heavy oil reservoir exploitation in the Western Canadian Sedimentary Basin is to produce emulsion into field production tanks from wells drilled on a high density pattern, often at ten to twenty acre spacing. The emulsion is then trucked to a centralized cleaning facility, where it is processed to pipeline specification of 0.5% BS&W and 350 centistoke viscosity in preparation for transportation to refineries. Pipelining the emulsion directly to the cleaning plants is generally not feasible due to the sand cut, high viscosity and entrained gas. The threat of bottom or side water breakthrough also introduces risk into the return on investment for pipelining.

Producing emulsion into field production tanks for trucking to cleaning plants has its own set of challenges. A property of low temperature heavy oil emulsion is high viscosity, which in turn lifts large amounts of sand and entrains gas with the oil. The entrained gas is in the form of expanding microbubbles that enhance fluid flow from the reservoir<sup>1,2</sup>. The microbubbles continue to expand in the tank, as the pressure drops to atmospheric. Here the gas slowly breaks out causing foam to sit on the oil in the tank. This foam layer can be several feet thick, increasing the risk of the tank overflowing and causing a spill. It also raises trucking costs by reducing the pay load. Cold viscous emulsion increases load/offload time, which also raises trucking costs.

**Emulsion Processing.** Heating the emulsion breaks down the foam, drops the sand to the bottom of the tank and separates the water out of the oil. Introduction of chemical de-emulsifier into the tank or gathering line can assist in this process. The type and amount of chemical is dependent on

water, clay and sand cut, oil characteristics, cleaning plant ownership and availability, water disposal options, etc. The apparent treating cost savings from reduced water cut may be outweighed by the increase in “slop” (tight interfacial emulsion) disposal costs that don’t surface for several weeks or months. The total costs must be included in the analysis. However, chemicals only enhance the process while heat is essential.

The heat source usually takes the form of a naturally drafted venturi style nozzle burner in a firetube. The burners nominally range in size from 75 to 300 kW (250,000 BTU/hr to 1,000,000 BTU/hr). The firetubes can be straight through (shotgun) or U-tube, and range from 100 to 300 mm in diameter. The nominal BTU rating refers to combustion capability, not the actual heat transfer. Burner manufacturers most often report combustion efficiency. The actual heat transfer is affected by liquid residence time, heat transfer surface area and fouling of this surface. The actual firetube heat transfer efficiencies are typically in the 35-65% range<sup>3</sup>.

An industry benchmarking study<sup>4</sup> reports utilities as the third highest cost driver. Tank heating can comprise one half of utility costs. Obviously low heat transfer efficiency raises operating costs, but it also greatly increases GHG emissions.

**Firetube Fouling.** A serious problem encountered with firetubes is fouling or coking which leads to the development of a “Hot Spot”. This hot spot normally occurs due to flame impingement baking the formation sands, clays, salts, asphaltenes, etc. on to the outside of the firetube. This coke product acts as an insulator preventing heat dissipation and eventually causing the metal to become so hot the tube collapses. This has the potential for personal injury or death, equipment damage and production loss. Fires have resulted due to the emulsion entering the firetube through cracks, and in some instances, the roof of the tank has blown off. In any case, significant costs are incurred cleaning up the spill resulting from the emulsion leak and replacing the damaged firetube. The tube we replaced for the pilot had significant buildup that we were unaware of. This tube likely would have failed within two months.

**Integrated Solution.** PanCanadian recognized these problems and implemented a firetube preventive management program in 1994. We also chose to use an integrated risk management approach to solve this problem. The integrated solution of the problem would:

- Lower Operating Costs
- Improve Safety
- Improve “Operability”
- Improve Loss Control Management
- Lower Green House Gas Emissions

Table 1) outlines the methodology of the Hazop Process we followed. Table 2) contains the results of the exercise that

compelled us to pursue heat pipe technology. (Appendix C provides a sample calculation to show how we arrived at cost of keeping emulsion at 85°C.)

PanCanadian started experimenting with heat pipe technology in 1989. Two heat pipe systems were installed in pressurized process vessels during 1994 with limited success. The application of this technology developed very slowly due to supplier economic stability, technology ownership issues and failures of heat pipes in unrelated industries. In 1996 PanCanadian approached HPC to develop an alternative heating system for our atmospheric heavy oil storage tanks. At the time HPC was a supplier of heat pipes for use in heat exchangers but not a manufacturer of an externally heated system. Working as a team, we set out to develop a thermosyphon process heater.

### Prototype Description

Gravity-assisted heat pipes or thermosyphons<sup>5</sup> are self-contained devices for thermal energy transport. They are characterized by their ability to transport heat at high rates over considerable distances, yet require only small temperature differences to drive the heat flow. The basic principles of thermosyphon operation are relatively simple. Referring to Figure 1, the working fluid inside a thermosyphon exists as liquid and vapor at nearly equilibrium thermodynamic conditions. During operation, two transport mechanisms exist – heat and mass transport. When a thermosyphon is exposed to heat source and sink, the working fluid equilibrates to an average saturation temperature and pressure. The temperature of the working fluid is nearly uniform throughout the tube between the temperatures of the heat source and sink. Heat addition causes the liquid within the tube to evaporate and enter the vapor phase. Heat removal at the condenser section condenses the vapor, returning it to the liquid state. This simultaneous influx and efflux of vapor creates the driving pressure differential for the nearly isotherm flow of vapor from the evaporator to the condenser. To complete this thermodynamic and transport cycle, the liquid or condensate must be transported from the condenser to the evaporator. Condensate return is accomplished via gravity force.

In 1996, HPC began development of the thermosyphon process heater for use in heavy oil storage tanks. This was a very challenging application of the technology given the stagnant fluid and temperature limits of 100°C within the storage tanks. Drawing on past and recent work on thermosyphon technology, in mid 1997 a prototype heater was designed and constructed.

The inherent design advantages of the thermosyphon process heater over naturally drafted venturi style nozzle burners include:

- External low pressure burner can utilize lower quality gas as a fuel source

- External burner and lower surface temperature of thermosyphons, is safer
- Higher effective heat transfer allows for quicker heat times, more consistent emulsion temperatures throughout the tank, lower operating costs and less GHG emissions

### Test Design

The field trial was designed using API Recommended Practices & API Standards to maximize the repeatability of the results. We chose a site at our Marwayne Field located in northeastern Alberta that had sixteen wells drilled on ten acre spacing, with eight wells producing into each of two 320 m<sup>3</sup> tanks. We proposed replacing one firetube with the thermosyphon prototype, allowing direct comparisons of performance by mitigating the effects of varying ambient temperature, inconsistent oil properties and differing production rates on the resultant data. Equipment specifications are summarized in Appendix A.

**Field Description.** The Marwayne Field is drilled into the Mannville group of zones at a depth of about 700 meters. The wells are drilled with slant rigs, keeping the boreholes as straight as possible to minimize tubing and rod wear. The oil is lifted using PCP 15-1400EL pumps (15 m<sup>3</sup>/d @ 1400 m head) with 22kW electric motors c/w VFD's. The two zones are commingled and yield an emulsion at surface of about 11° API and 35,000 cP viscosity. Emulsion temperature at surface is 27° C. The sand cut ranges from up to 30% initially, to 1-3% after flow stabilization in one to three months.

### Test Objectives

Prior to test initiation, HPC and PanCanadian met to confirm that each company's objectives were mutually attainable. The field test was designed to ensure operability and to provide information about the equipment specifics.

Here is the compiled list of test objectives that we intended to establish:

- overall thermal efficiency (fuel based)
- heat input and heat transfer rates (tank emulsion heating)
- firing, safety, environmental and operating cost improvements by implementing the prototype for indirect heating with burner equipment firing outside the storage tank causing less coking/build up on firetubes
- operational advantages in implementing thermosyphons for transferring heat into the tank with high rate of sand deposits
  - ◆ better temperature control of emulsion
  - ◆ quicker emulsion heating times
  - ◆ improved burner reliability
- energy conservation, fuel saving and decreased CO2 and NOX emissions on equipment burners
- ability to burn solution gas with no significant decrease in preceding objectives

### Test Procedure

The thermosyphon prototype was assembled at the manufacturer's Beasley, Texas facility. The unit was designed for retrofit installation into the 320 m<sup>3</sup> atmospheric storage tank through the existing 300 mm firetube flange. Thermosyphon performance was verified by testing the prototype for equipment and control system operability in a tank simulator at the Beasley site in Oct '97. The simulation was successful, and the prototype was shipped.

The prototype was installed at the field site on November 13, 1997. The assembly and installation of the unit took about six hours using a maintenance crew, picker truck and a welder. We were very pleased with the time considering this was the first time the operations personnel had seen, let alone handled this equipment. As a prototype, the thermosyphon employed a number of features to ensure test reliability, which increased the size of the unit. Plans are already underway to reduce the size of the external heat processor. In future, standardized flanges and procedures could further shorten the installation time.

The testing was scheduled to run approximately three months. Preparation for and testing was carried out according to API RP #532, Sect 2, Par. 2.1 & 2.2. The following measurements were taken during the test using API RP #532, Par. 15:

- Fuel flow rate
- Process flow rate
- Process fluid inlet temperature
- Process fluid outlet temperature
- Process fluid inlet and outlet pressure
- Fuel pressure at the burner
- Flue gas draft profile

To evaluate firing, combustion, heat generation and heat transfer performance of the thermosyphon, a testing method was developed in four stages. In stage 1, we would monitor the flue gas side and measure: fuel gross efficiency; net efficiency in the fire box; and, combustion efficiency. Expected duration was one week. In stage 2, we would monitor the process side and measure: heat transfer; and, heat absorbed by the process. Expected duration was one week. In stage 3, we would monitor overall heat balance and measure: combustion efficiency, heat transfer efficiency, and relative waste. Expected duration was five weeks. In stage 4, we would burn solution gas normally vented to atmosphere up the casing. Expected duration was six weeks.

Stage 3 & 4 ran extended times to gain experience operating the prototype under field conditions and allow for optimization of:

- Available heat/ radiant-convection section
- Heat picked up by process / liquid in pipes
- Distribution of heat in lowest row and in between pipes
- Flue gas circulation and distribution in between pipes at different bundle height inside the fire box

- Stack draft and damper effect
- Size and equipment dimensions to optimize heat transfer

## Evaluation

The performance testing compared tank operation, temperature and energy consumption between the thermosyphon process heater installed in tank “A” and the firetube and natural draft burner in tank “B”. The objective was to compare and investigate Tank A and Tank B operation by evaluating the following steps:

1. Fuel Consumption - Measuring the differences in operating Tank A vs. Tank B by maintaining the product in tanks at the same temperature level.
2. Temperature Gain - Compare operating temperatures in Tank A vs. Tank B at the same rate of fuel input comparing temperature increase and response time.
3. Operational Difference - Compare Tank A vs. Tank B by firing each tank at its maximum firing capacity and measuring the CO<sub>2</sub> and NOX emissions, coking/buildup, equipment reliability.

Performance and operability of the thermosyphon was evaluated according to API Standards and Recommended Practice issued for fired heaters covering the subjects:

- ❖ Measurement of the Thermal Efficiency on Fired Process Heaters - API RP #532 (Aug '82)
- ❖ Fired Heaters for General Refinery Services - API Standard #560 (Jan '86)
- ❖ Instrumentation and Control System for Fired Heaters And Steam Generators - API RP #556 (May '97)
- ❖ Process Analyzers - API #555, 550 part II

The flue gas was analyzed according to API RP #532, Par. 1.4.2 using a portable analyzer for oxygen and combustible gases.

The measured data was interpreted for GHG emissions using VCR Reporting Guideline Rev 98/April/8, published by the Canadian Association of Petroleum Producers (CAPP). The portion of the report containing relevant information is reproduced in Appendix B. This report converts total greenhouse gases to a carbon dioxide equivalent (CO<sub>2</sub>E).

All parameters, fuel consumption, temperature and firing capacity were recorded on survey forms and the tank heating efficiency was calculated using computer models and heat balance calculation forms developed by HPC. All activities including collection of data and analysis were conducted according to a Standard Practice Manual certified under ISO 9001. The objective of this quality management system is to ensure that all project work is performed on time and within budget and the project will achieve the intended R&D objectives and is understood, and, if necessary could be reproduced successfully by others.

## Test Results:

Table 3) summarizes the results. Appendix C provides some sample calculations. The thermosyphon process heater had a combustion efficiency of 83%, which is extremely high for a naturally drafted burner. This was 25% higher than the firetube burner. The effective heat transfer was double that of the firetube system. The prototype burned 33% less fuel while providing more heat to the emulsion. GHG emissions were reduced by 5,000 tonnes per year.

Please note that in this test we adjusted the firetube burner on a weekly basis to maintain maximum combustion efficiency. Most field tank burners are lucky to receive annual tune-ups. For each 1% drop in combustion efficiency, the CO<sub>2</sub>E increases by 2%. Or, given the above fuel rates, a fire tube burner at 50% combustion efficiency would have a 30% higher CO<sub>2</sub>E than we reported. This assumes there is no increase in fuel consumption due to decreased heat transfer effectiveness. There are several operators who use two fire tubes per tank to achieve the required heat input.

We were forced to make one change after initial results were analyzed. In designing the test, we overlooked the fact that the water cut in the emulsion going in to each tank was significantly different. Therefore we added a step to the test by switching which tank and burner system the emulsions flowed into. This required some mechanical rework of the gathering lines and extended the test one month, but it did verify the initial test results.

In the last phase of the pilot, we burned solution gas in the thermosyphon process heater that is normally vented to atmosphere out the casing. The heating value was fairly similar to the fuel gas we were purchasing, but being solution gas, it was much richer. The richness and moisture content of solution gas normally causes problems in the nozzles of firetube venturi burners. We experienced no operational problems and the thermosyphon process heater performance was equivalent to using commercial gas. The GHG emission reduction in this case is 10,000 tonnes per year.

## Summary:

All objectives of the pilot were met. PanCanadian Petroleum Ltd. is very pleased with the THERMFLO™ Tank Heater supplied by Hudson Products Corp. Perhaps the most significant measure of the success of this pilot is operator endorsement. From the day the unit was fired, it has performed trouble free and beyond all expectations. The unit is operator friendly, safe and efficient. The prototype is still in use. It has the potential of saving about \$40,000 per year in fuel gas costs on this pad, and is the equivalent of parking 9 cars per BOPD.

## Acknowledgments

We thank Bob Giammaruti, George Millas and F.G. Russel with HPC for valuable discussions on the interpretation of the

pilot results and strong R&D support; Jack Whittaker, Steven Lee, Jody Kissick and Dale Cussack with PanCanadian for their assistance in executing the pilot, and their helpful feedback.

## References

1. Claridge, E.L. and Prats, M.: "A Proposed Model and Mechanism for Anomalous Foamy Heavy Oil Behavior", paper presented at the International Heavy Oil Symposium held in Calgary, Alberta, Canada, 19-21 June 1995.
2. Geilikman, M.B., Dusseault, M.B., and Dullien, F.A.L.: "Dynamic Effects of Foamy Fluid Flow in Sand Production Instability", paper presented at the International Heavy Oil Symposium held in Calgary, Alberta, Canada, 19-21 June 1995.
3. Ferguson, K.R. and Stechmann, R.H., "Improving Heater Treater Fuel Efficiency", Journal of Petroleum Technology, June 1980.
4. Ziff Energy Heavy Oil Benchmarking Study, 3<sup>rd</sup> Edition, May 1996
5. Fagri, A., Chen, M.M., and Mogan, M., "Heat Transfer Characteristics in Two-Phase Closed Conventional and Concentric Annular Thermosyphons," ASME J. Heat Transfer, Vol 111, pp. 611-618, 1989.

## Metric Conversion Factors

1 mm = 0.03937 in  
 1 m = 3.281 ft  
 1 m<sup>3</sup> = 35.31 ft<sup>3</sup>  
 1 m<sup>3</sup> = 6.29 bbl  
 1 kg = 2.2 lb  
 1 tonne = 1,000 kg  
 1 tonne = 2,200 lb  
 1 kg/m<sup>3</sup> = 0.001 g/cc  
 °C = 5/9 °F  
 x°C = 5/9 (°F-32)  
 1 kW = 3,412 BTU/hr  
 1 kW = 1.341 HP  
 1 GJ = 1,000 SCF of natural gas  
 1 kPa = 0.145 psi

## Appendix A Equipment Specifications

Thermosyphon Process Heater Design and Specifications

Manufacturer HPC Products Corporation, a McDermott company  
 Model THERMFLO™ Process Heater TH-2000  
 CRN OH2329.2  
 Heat Duty 390 kW (1.3 MMBTU/hr)  
 Firing Capacity 540 kW (1.8 MMBTU/hr)  
 Size 1143mm x 1676mm x 2083mm  
 45"W x 66"L x 82"H

Gas Side (Evaporator)

flue mass 1364 kg/hr (3000 lb/hr)  
 inlet air @ 5° C (40° F)  
 heat / natural gas 37 mJ/m<sup>3</sup> (1000 BTU/CF)

Firing Components (Burners)

16 ea. low press, model natural gas / up-shot  
 1 pilot burner, model natural gas / Can-Alta 501

Liquid Side (Condenser)

Heat Exchanger bundle Thermosyphon

Storage Tank

Manufacturer GLM Tank Manuf., Nisku, Alberta  
 Model J-96-109-S1  
 Vessel Size 7.2m Dia x 7.9H m (23.5' Dia x 26' H)  
 Vessel Volume 320 m<sup>3</sup> (2000 bbl), cone bottom

Firetube Burner

Manufacturer Enardo  
 Model FAB-24-12 7/32" orifice  
 Firing Capacity 300 kW (1MM BTU/hr)

## Appendix B

Greenhouse Gas Conversion Factors – from Canadian Association of Petroleum Producers (CAPP) Voluntary Challenge Registry (VCR)

### Relative Impact of Greenhouse Gases on Warming Effect:

The following is a list of GWP factors (GWP<sub>100</sub> means the 100 year Global Warming Potential) which take into account the relative impact of different greenhouse gasses on the atmosphere and the differing lengths of time they reside in the atmosphere:

CO<sub>2</sub> = 1 (life in atmosphere = 50-200 years)  
 CH<sub>4</sub> = 21 (life in atmosphere = 10 years)  
 N<sub>2</sub>O = 330 (life in atmosphere = 130 years)  
 CFC = 2000-6000 (life in atmosphere = 55-400 years)

The factors are used to convert non-CO<sub>2</sub> greenhouse gas to an equivalent CO<sub>2</sub> mass (termed CO<sub>2</sub>E).

### CONVERSION TO CO<sub>2</sub>E:

The following conversions take into account the differences in global warming potential and density of gases, and the effects of combustion (i.e., venting vs. flaring for methane, and CO<sub>2</sub> emissions from electric power generation).

Methane: Flare versus Vent

1 MMSCF = 53 tonne CO<sub>2</sub>E if Flared  
 = 402 tonne CO<sub>2</sub>E if Vented

1 E<sup>3</sup>m<sup>3</sup> = 1.89 tonne CO<sub>2</sub>E if Flared  
 = 14.28 tonne CO<sub>2</sub>E if Vented

1 E<sup>3</sup>m<sup>3</sup> CO<sub>2</sub> = 1.89 tonne CO<sub>2</sub>

1 E<sup>3</sup>m<sup>3</sup> CH<sub>4</sub> = 0.68 tonne CH<sub>4</sub> = 14.28 tonne CO<sub>2</sub>E

Notes:

(i) there is a 7.6:1 ratio of venting versus flaring

(ii) units: kt = kilotonne = 10<sup>3</sup> tonnes

(iii) the flaring CO<sub>2</sub>E conversion includes combustion by-products

### Power (from utility company):

1 KW-HR = 3412 BTU/HR = 1 kg CO<sub>2</sub>E  
 = 0.001 tonne CO<sub>2</sub>E

Note: approximate rule-of-thumb for Alberta or Saskatchewan where electric power is coal generated.

### Appendix C Sample Calculations

#### A) Cost of keeping tank emulsion @ 85°C vs. 65°C

$$\begin{aligned} & (\text{Prod'n})(\text{Spec Heat})(\Delta T)(\text{Density})(\text{Cost/GJ})(1\text{GJ}/1000\text{kJ}) \\ & = (80\text{m}^3/\text{d})(1.9\text{kJ}/\text{kgC})(20\text{C})(1000\text{kg}/\text{m}^3)(\$2/\text{GJ})(1\text{GJ}/1000\text{kJ}) \\ & = \$64/\text{day} \\ & = \$23,000/\text{yr} \\ & \text{Add } \$36/\text{day} \text{ for heating water phase and heat loss} \\ & \text{out the tank} \\ & = \$100/\text{day} \text{ or } \$36,500/\text{yr} \end{aligned}$$

#### B) Fuel Gas Consumption

$$\begin{aligned} & (\text{Measured GJ/hr})(24 \text{ hr/day})(365 \text{ day/yr}) \\ & = (2350)(24)(365) \\ & = 20.6 \text{ MMSCF/yr} \\ & \text{Note that 1 mscf is approximately equal to 1 GJ.} \end{aligned}$$

#### C) CO<sub>2</sub>E Calculations

$$\begin{aligned} & \text{CO}_2\text{E of Flared Gas} \\ & (\text{Annual Fuel Gas})(\text{Combustion Efficiency})(53) \\ & (20.6\text{mmscf})(0.65)(53) \\ & = 709 \text{ tonnes/yr CO}_2\text{E} \end{aligned}$$

$$\begin{aligned} & \text{CO}_2\text{E of Unburned Gas} \\ & (\text{Annual Fuel Gas})(1-\text{Combustion Efficiency})(402) \\ & = (20.6\text{mmscf})(0.35)(402) \\ & = 2896 \text{ tonnes/yr CO}_2\text{E} \end{aligned}$$

Table 1) Hazop Methodology

|               |   |
|---------------|---|
| Impact Rating | Probability   |
| 1 – Minor     | A – Remote: Not likely to occur during life cycle, or none expected for the system being assessed                       |
| 2 – Moderate  | B – Occasional: Likely to occur sometime during life cycle, or 1 to 3 occurrences over a 30 year life cycle             |
| 3 – Serious   | C – Probable: Likely to occur several times during life cycle, or 4 to 9 occurrences over a 30 yr. Life cycle           |
| 4 – Major     | D- Frequent: Happens often and might be expected during life cycle, or 10 or more occurrences over a 30 year life cycle |

The impacts are divided into four categories, with the highest impact being the overall risk.

P – People

E – Environment

A – Assets

I – Image

|        |             |   |   |   |   |
|--------|-------------|---|---|---|---|
| Impact | 4           |   |   |   |   |
|        | 3           |   |   |   |   |
|        | 2           |   |   |   |   |
|        | 1           |   |   |   |   |
|        |             | A | B | C | D |
|        | Probability |   |   |   |   |

|  |   |
|--|---|
|  | <b>EXTREME RISK</b> – Cannot accept risk. Stop activities unless risk controls that will move activity out of extreme risk are immediately implemented. |
|  | <b>HIGH IMPACT RISK</b> – Must implement extensive risk controls.   |
|  | <b>MODERATE RISK</b> – Some risk controls required.   |
|  | <b>LOW RISK</b> – Some risk controls may still be justified.  |

Table 2) Hazop Summary

| I.D. Hazardous Concerns  | Probability | Probability Reasoning  | Impact                   | Impact Reasoning  | Overall Risk | Risk Controls  | Residual Risk |
|--|-------------|--|--------------------------|---|--------------|--|---------------|
| Replacement of Firetube  | D           | - Historical Data<br>- Informal Survey of Competitors                      | P-1<br>E-1<br>A-1<br>I-1 | - Cost includes new tube, removing liquid from tank, labor to remove tube<br>- This does not include cost of loss production or physical damage to tank                     | A-1          | - Closely monitor sand production & build up in tank<br>- Monitor tank temp response against temp control adjustment | A-1           |
| Lost Production  | C           | - Historical Data<br>- Pads with 2 tanks & crossover valve aren't affected | P-1<br>E-1<br>A-1<br>I-1 | - 8 well pad will produce about 200 m3 @ \$75/ m3 of oil over 3 days that it would take to replace tube<br>- 25% of pads will allow wells to produce while tube is replaced | A-1          | - Same as above<br>-   | A-1           |
| Emulsion spills out cracked tube   | D           | - Historical Data  | P-1<br>E-1<br>A-1<br>I-1 | - Historical data indicates about \$1500/spill<br>- It is usually oil that spills out, not water, so viscosity of heavy oil limits environmental contamination              | E-1          | - Same as above<br>-   | E-1           |
| Tank Explodes  | C           | - Historical / Industrial Data   | P-4<br>E-1<br>A-1<br>I-1 | - Largest danger is to personnel, incl. 3rd party (truck drivers, etc.)<br>- 750 bbl = \$25k<br>- 1000 bbl = \$32k<br>- 2000 bbl = \$60k                                    | P-4          | - Same as above, Plus<br>- Follow proper procedures offloading, lighting burner etc.<br>- Perform annual inspections | P-1           |
| Lack of efficient heat transfer promotes foaming & requires higher operating temperature | C           | - Historical data  | P-1<br>E-1<br>A-1<br>I-1 | - \$25,000/yr Can<br>- \$35,000/yr Can incl. water and heat loss<br>- steam clean tank & clean up spill, \$1,000 Can<br>- trucks charge more for less dense payloads        | A-1          | - Use more than one firetube<br>-  | A-1           |
| Firetube unreliability – pilots blow out   | D           | - Historical data  | P-1<br>E-1<br>A-1<br>I-1 | - oil cools off, foam builds up, spills over<br>- operator's time wasted relighting pilots  | A-1          |  | A-1           |

Table 3) Test Results

|   | Thermosyphon using casing gas | Thermosyphon using fuel gas | Fire Tube                 |
|---|-------------------------------|-----------------------------|---------------------------|
| Combustion Efficiency (%)   | 83                            | 83                          | 65                        |
| Total Heat Input – kW (mmBTU/hr)                                  | 350 (1.20)                    | 350 (1.20)                  | 250 to 450 (0.84 to 1.55) |
| Heat Effectiveness (%)  | 55                            | 55                          | 27                        |
| Fuel Gas Consumption Measured (scfh)                              | 1550                          | 1550                        | 2350                      |
| Annual Gas Consumption (mmscf)                                    | 0                             | 13.6                        | 20.6                      |
| <b>Annual Fuel Gas Cost @ \$2/mscf Can</b>                        | <b>0</b>                      | <b>\$27,156</b>             | <b>\$41,172</b>           |
| CO <sub>2</sub> E Flare (tonnes/yr)                               | 597                           | 597                         | 709                       |
| CO <sub>2</sub> E Not Burned during combustion (tonnes/yr)        | 928                           | 928                         | 2896                      |
| CO <sub>2</sub> E Vent (tonnes/yr)                                | 0                             | 5467                        | 8281                      |
| Total CO <sub>2</sub> E (tonnes/yr)                               | 1525                          | 6992                        | 11886                     |
| Normalized Total CO <sub>2</sub> E (tonnes/yr per BOPD)           | 5                             | 23                          | 40                        |
| <b>Equivalent number of passenger cars versus annual emission</b> | <b>1</b>                      | <b>5</b>                    | <b>10</b>                 |

\* NRCan states a typical car emits 4 tonnes/yr of pollutants.

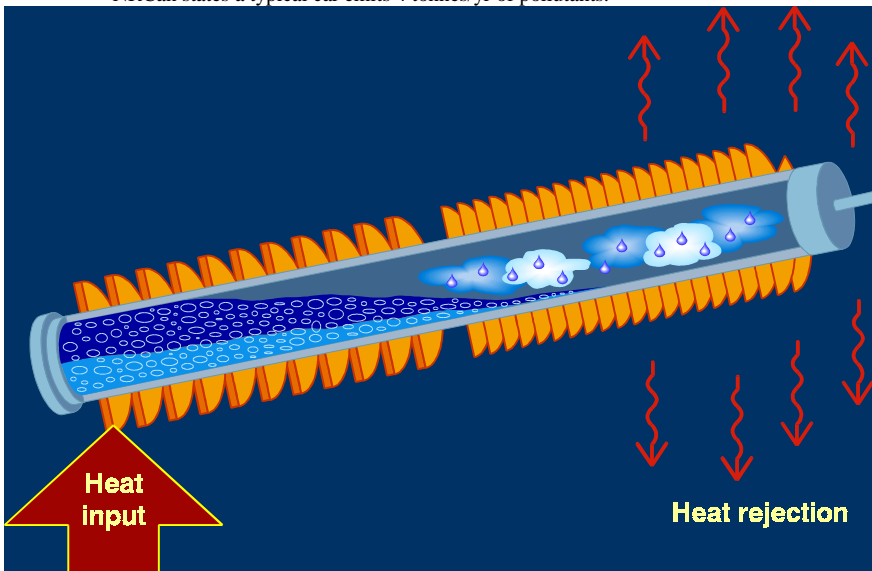


Figure 1. Gravity-Assisted Heat Pipe or Thermosyphon