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Howard Pedolsky
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Stuart Fedder
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Konstantine Gavrylov
Eco-Fridge Production

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Howard Pedolsky\textsuperscript{1}, Stuart Fedder\textsuperscript{2}, Konstantine Gavrylov\textsuperscript{3}

\textsuperscript{1}Ukram Industries, President
Bethesda, Maryland, US
\textsuperscript{2}Ukram Industries, CFO
Bethesda Maryland, US
\textsuperscript{1} & \textsuperscript{2}Tel: (301) 280 3572 Fax: (301) 942-2734
e-mail: Ukram1a@aol.com
\textsuperscript{3}Eco-Fridge Production Company, Director
Kharkov, Kharkov Ukraine
Tel: (380) 572 587-480, Fax: (380) 572 587-481
e-mail: Konstantin@ecofridge.info

1. Abstract

\textsuperscript{2}conditioning is an innovative, cost effective and practical method for providing the required environment for transportation of food produce and other products, which have specific temperature demands. In order for any new system to be economically viable it must compare favorably with existing systems. Systems in the past consumed too much \textsuperscript{2}, the cost of \textsuperscript{2} was much too high and the availability of \textsuperscript{2} was limited.

Over the last several years Ukram has proven the practicality of such a system. The system we developed has been successfully road tested by several major produce. It has received significant support from two major \textsuperscript{2} supply companies.

During the test period we have had to validate several salient features of our system:

- User friendliness
- Safety
- Economic competitiveness
- Environmental friendliness

In order to demonstrate the latter two features we had to consider the total system, including end-to-end production and ready availability of \textsuperscript{2}. Production is defined as, not only the production of the Nitrogen Conditioning System (NCS) but also production of \textsuperscript{2}.

To prove the economic competitiveness of our system we had to consider the cost of the NCS, the cost of \textsuperscript{2}, the maintenance of the NCS over time and the cost of operating the system. This paper will focus on the reliability, maintenance and operation of the NCS, which must be considered to make a system such as this commercially viable. Figure 1 depicts the eco-Fridge NCS.

Figure 1. NCS System
2. Introduction

There has been a recent development of an innovative refrigeration system, which is applicable for transportation of refrigerated, frozen and multi-temperature cargo over road, on water and over rail. The cryogenic system uses $N_2$ as its refrigerant.

Many years ago such a system was attempted but it failed primarily for economic reasons. The cost of $N_2$ was prohibitive and its availability was limited. After much money was spent attempting to implement such a system or variants such as $CO_2$, it was left in abeyance. In addition, the designs for the distribution of $N_2$ were inefficient, resulting in a consumption, which prohibited more than one day’s supply with a reasonably sized storage tank. Finally, the size and quality of the tanks were constrained by the prohibitive cost and poor technology of the storage tanks.

Recently, with the rise in the cost of fossil fuels and the ready availability of $N_2$, new attempts have been made to implement cryogenic systems. There has been an environmental impetus as well to look for variants of refrigeration systems away from fossil fuels. A nitrogen conditioning system (NCS) has recently been road tested by several major produce companies. As a result of the tests, there has been an economic analysis made comparing mechanical, fossil fuel, HCFC systems with the NCS system.

This paper will provide a report of that comparison and will provide the implications of the results.

3. Discussion

The economic analysis of the cryogenic refrigeration system with the mechanical fossil fuel/HCFC system is composed of the following elements:

1. Material and manufacturing costs
2. Operational costs
3. Fuel or working fluid cost
4. Lifetime costs
5. Maintenance costs

3.1 Design Features Leading to Economic Improvement of Cryogenic Systems

Several decades ago there was a serious attempt by the produce industry to use cryogenic systems of various types, $N_2$ and $CO_2$ being two of them. Technically, the systems were not designed efficiently nor were the systems operated efficiently. Finally, the cryogenics were expensive.

3.1.1 Tanks

Cryogenic tanks design is very complex. Internal structure, insulation, vacuumization, internal tubing and several other features must be perfectly accomplished or the tanks will lose an exorbitant quantity of LNG. The rates of loss were in excess of 5 liters per hour. Today, the storage tanks being used in the NCS lose less than 2 liters per hour.

The size of the tanks is also critical. Filling LNG at low pressure is not a rapid operation. Large tanks must be used. However, the cost of a large tank can be prohibitive. This cost had to be overcome.

3.1.2 Sprayers

Sprayers control the distribution of the cryogenic substance. Previously the distribution was simple and very inefficient. Channeled flow was used. Today’s system uses a very complex distribution pattern. It increases the rate of cooling significantly, thereby, reducing the use of the cryogenic substance. We can now pull down temperature in the trailer at a rate of approximately 150% faster than the mechanical systems.

3.1.3 Control sensors

There was single zone control inside the trailers previously. This resulted in unbalanced cooling and thereby resulting in frozen produce where frozen produce would be thrown away, again resulting in increased total cost. Now we have multi-zone distribution with independent sensor control. This results in extremely balanced cooling.

3.1.4 Cryogenic liquids
LNG availability, many years ago along with other cryogenic fluids was not readily available. The result of the limited availability and the lack of competition at the national level resulted in a very high cost. The cryogenic fluid contributes almost 50% of the total cost of the system. Today the cost of the fluids, especially LNG has been reduced by 200%. In addition, LNG is now produced in 48 states. The two states not producing LNG are actually in the lower 48, Idaho and N. Dakota. LNG is now produced in Alaska and Hawaii. This also allows the user to reduce his storage capacity size since delivery could be increased easily as needed.

3.2 Comparison of Costs

3.2.1 Variables considered in the comparison

The comparison is not simple and it is not always a direct comparison.

- For instance, the mechanical systems have a growing rate of maintenance as the system ages. The cryogenic systems do not. Do we compare new system to new system? Not necessarily. Doing this implies the lifetimes are equivalent and the maintenance cost for the cryogenic system increases with age in a similar manor to the mechanical system. This is not a good assumption. Do we compare the two systems, new for the NCS versus mid-life system for the mechanical system? Maybe a better assumption, but is it realistic? Do we compare the two, new versus old, probably to much in favor of the cryogenic system. As can be seen, the comparison assumptions are not easily established.

- Another comparison, which is not easily made, is the operational cost comparison. This comparison is weighed heavily by the cost of fueling. How do we make this comparison? The fueling cost for each must take into account:
  - Method of fueling the mechanical system
  - Requirement for fueling or loading LNG
  - The dedicated time required of the fueling staff for both

- Cost of fuel
  - Diesel fuel varies with all fuel costs which varies with:
    - Location
    - Crude oil prices
    - Season
  - LNG varies with:
    - Cost of electricity
    - Proximity to LNG production site

- Cost of raw materials
  - The most cost critical part of the cryogenic system is the cost of the cryogenic tanks
    - Aluminum can vary more than 30% over a short period of time.
    - Cost of energy required to operate the manufacturing site.
  - The most cost critical part of the mechanical system is the cost of materials and parts for the diesel sub system.

Above are just an example of the parameters and the variances, which must be considered.

For the cryogenic system costs we based our assessment on a combination of empirical data, actual data and projected costs.

3.2.2 Cost Assumptions for Comparison

- Maintenance; mid-life mechanical system; 3-5 years
- Maintenance new NCS (no maintenance based on age)
- Unit cost NCS
  - Base cost for order of 100 units
  - Optional cost – heater; O₂ detector
  - Additional in-line batteries
- Unit cost mechanical system
  - Single temperature system
  - Optional cost for multi-temperature capability
- Projected lifetime
  - Seven (7) years for mechanical system
  - Twenty (20) years for NCS
- Operational Labor costs
  - Diesel filling – 5 minutes
LNG filling – 10 minutes
- Cost for diesel tank - $0 (no additional cost from cost for tractor)
- Cost for LNG storage tank
- Diesel cost
- LNG cost
- An interesting but difficult element, which must be taken into consideration, is how operating time per year is computed.
  - The mechanical systems operate on a cyclic basis and the time is computed by assessing engine on off time.
  - How is a cryogenic system operating time computed? It also operates on a cyclic basis but the cyclic components are the control valves. These do not operated synchronously. Therefore it is impossible to measure the on-off time for the cryogenic system. It must be assumed the system is operating continuously. This is not realistic and it can result in misleading results.

### 3.2.3 Cost Matrix Mechanical System

<table>
<thead>
<tr>
<th>Variables</th>
<th>Operating Time per Yr (hrs)</th>
<th>Cost per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Unit cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Projected Lifetime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Operational labor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Fuel cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Total operating costs (new to 3 year life for single temperature refrigeration system)</td>
<td>$1.80 - $2.25</td>
<td></td>
</tr>
<tr>
<td>• Total operating cost for a multi-temperature new system</td>
<td>$2.20</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2.4 Cost Matrix Typical Open Cryogenic Refrigeration System

<table>
<thead>
<tr>
<th>Variables</th>
<th>Operating Time per Yr (hrs)</th>
<th>Cost per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Unit cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Projected Lifetime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Operational labor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Fuel cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Total operating costs (Based on quantity ordered; not sensitive to age)</td>
<td>$1.60 - $1.80</td>
<td></td>
</tr>
<tr>
<td>• Total operating cost for a multi-temperature cryogenic system</td>
<td>$1.60 - $1.80</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2.5 Cost Summary

It is very clear that under nominal conditions there is not much to choose between mechanical and cryogenic systems. The separation in economic advantage occurs when the end user requires a multi-temperature refrigeration system. Under these conditions the mechanical system cost is increased approximately 50% but cryogenic system does not vary at all.
4. Summary

4.1 There are many variables, which must be considered when moving to a new technology.
- Environmental
- Safety
- Operational friendliness
- Economics

4.2 The variable, which seems to have the most influence as a deciding factor for companies to decide to move to any new technology is economic variable. Other considerations will have a strong influence, such as environmental factors, ease of operation, et al. However, without economic competitiveness corporations will rarely move to new technologies. Design must consider this at every step. In addition, the economic analysis must be done concurrently between the user and the supplier. Many of the factors, which are considered, vary from user to user. Each must do the assessment based on his own operational system and his method of maintaining cost to operate.