CRAFT
SYNTHESIS REPORT

CONTRACT' NO. **CR-1569-91**
PROJECT NO. BRE2.CT94.1513

SOLAR POWERED REFRIGERATOR FOR DEVELOPING COUNTRIES

Project Co-ordinator	**QUEST REFRIGERATION MANUFACTURING LTD, UK**
SME Partners	**ALTEN SRL, ITALY** **INDEL B SRL, 1TAL%** **UA EXTRUSIONS LTD, UK**
R&D Partners	**CRANFIELD UNIVERSITY** **ISTITUTO GIORDANO** **CNR LAMEL LABORATORIES** **BARTOLI (UK) LTD** **EUROPUS LTD** **ANCHEM LABORATORIES** **FGHLK STUTTGART MBH**

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2. Title: Solar Powered Refrigerator for Developing Countries

Author: Philip E P Bacon
Europus Ltd
Apex House
Wonastow Road
Monmouth, Gwent. NP5 4HL UK
Tel: +44 1600715311
Fax: +44 1600714234

or: C/O Quest Refrigeration Manufacturing Ltd
Aber Park
Flint
Flintshire, North WalesCH65EX UK
Tel: +44 1352762300
Fax: +4 1352735795

3. Abstract

The requirement for basic health improvements in the developing countries can be greatly assisted by the use of cool storage for vaccines and perishable goods. In addition, there is an increasing requirement in the developing countries for refrigerators, as a natural development whilst there is also at present, inadequate power supplies. Due to potential worsening pollution effects, it is not in the interests of the rest of the world, to provide that power and many of these countries have adequate solar isolation. In the "Western/Developed countries 25-3 5% of all power is used for refrigerators and deep freezers. This is also of serious concern and technologies developed can be utilised for reducing this increasing problem.

This project undertook to develop technologies which optimised and reduced the energy requirements for **solar powered refrigerators** in order that greater numbers of organisations and communities in the developing countries could afford a refrigerator which had a long life and was reliable.

Insulation technology, coolth storage, battery selection for deep discharge and low maintenance, compressor/ heat pump performance improvement combined with logic charger/controller design have been optimised. This has resulted in plastic (recyclable) prototype refrigerators which have been built and tested and found to provide a cost effective solution, reducing the size of the solar panels and batteries. These are the major costs elements of a solar powered refrigerator.

The project has successfully created a number of technologies which can be used to reduce the overall cost/performance ratio of a solar powered refrigerator but can also be beneficially used in high specification conventionally powered refrigerators for different markets.

4. Introduction

There is a natural interest and requirement throughout the world to improve the living standards and health of the people of the developing countries and at the same time be aware of the commercial potential of supplying goods to achieve this. This project has recognised that refrigeration is one of the basic helps towards increasing the overall health of communities and that the peoples of the developing countries are beginning to require them as part of that development as their wealth increases. Unfortunately many of the areas of these countries do not have the electrical power to power conventional refrigerators and it may not be wise, due to the potential increase in atmospheric pollution, for additional power capacity to be installed. In the European market, the order of 25-3 5°/0 of all electrical power goes to power refrigerators and deep freezers with the average number of refrigerators in the UK south eastern area being 1.7 per household. In Southern Germany and Italy the figure will be higher. Most of the developing countries have the greatest potential for the use of Solar Energy.

This project has recognised that the solar power refrigerators at present supplied mainly by the World Health Organisation, are built to a very high standard and are costly at approximately $6,000 each (39litre). From investigations it appeared that the refrigerators were not designed specifically for the task but were loose items of high specifications brought together to achieve the required performance. This results in their high cost.

This project has sought to optimise the various technologies of insulation, cool energy storage, heat pump (compressor, evaporator, condenser), control discharge system and battery technology so that the overall cost per performance is reduced to a target price of £3,000 sterling per refrigerator (39 litre). The exception which did not receive R&D attention, was the photo voltaic cell which is receiving world wide attention and was beyond the scope of this project.

The team assembled, comprised the complimentary skills of companies involved in the manufacture of refrigerators, refrigerators components, solar power components and systems. The R&D organisations were specialist in thermodynamic modelling, testing, coolth storage, battery technology, tooling development and European project management. The team members were:

The R&D performers were:
Cranfield University has excellent knowledge and experience in the design and modelling of thermal and hydrophilic heat transfer systems.
CNR Lame] is experienced in the design and prototype manufacture of electronic control systems and has worked closely with Alten srL to produce the controller/charger.
Istituto Giordano has tested the cooling system components and systems for heat pump system selection in order to increase the Coefficient of Performance(COP).
Anthem labotaories with NEB Associates co-ordinated the battery development initially and changed to battery selection at the mid-term point of the project.

Bartoli (UK) Ltd has carried out the development of the tooling and insulation to produce with Quest Refrigeration Manufacturing Ltd a successful refrigerator cabinet with very low thermal loss/gain.
Europus Ltd has provided the overall and detail project co-ordination with Quest Refrigeration Manufacturing Ltd.

The companies involved were:

Quest Refrigeration Manufacturing Ltd, the project co-ordinator who is a manufacturer of novel plastic refrigerators.
Indel B srL who is a manufacturer of DC compressor and associated heat pump components and who also makes small refrigerators for niche markets.
Alten srL who is a supplier and manufacturer of solar systems for a wide variety of end uses.
Oakdale Batteries Ltd A battery manufacturer but who entered into receivership at the mid -term point of the project. They were replaced by UA Extrusions Ltd.
UA Extrusions Ltd area supplier and manufacturer of aluminium extrusions for door frames for refrigerators and shop front systems.

5. Technical Description

5.1 Model

Due to the complexity of the potential market and of the number of variables Cranfield University developed a model bringing together the unit prices of the various elements of the solar powered refrigerator and their performance characteristics. This model has been used throughout the project to establish the physical parameters and the potential loading requirements and sizing of the battery, The model could be further developed to show the transient responses but at this stage has been found adequate for the requirements. The model will be used by the SME partners for future designs.

Various operating strategies were also investigated to assess the most beneficial (Iow energy) process. This was found to be the continual operation of the heat pump with an internal static cool cell.

Detail designs of cool cells were provided by Cranfield University for 39 and 110 litre refrigerators as well as detail analyses of static and dynamic COOI ceil performances.

5.2 Insulation

The model showed fairly quickly that the insulation thickness required would increase the surface area dramatically and hence reduce its overall effectiveness. An improved form of insulation needed to be developed and the vacuum filled panels provided by Owens-Corning of USA, which is a super fibreglass insulant wrapped in a stainless steel vacuum case, was explored.

Techniques were developed to utilise this material with the outer and inner plastic sheeting of the Quest cabinet and successful trial boxes manufactured for test at Cranfield University. The model was up-dated with the new mid-panel insulation factor and also the increased COP factors at 24°C and 35°C from Istituto Giordano test on the Compressor/heat pump systems.

5.3 **Compressor with evaporator and condenser**

Indel B have already in production, a compressor with an asynchronous three phase squirrel cage motor with a 24V DC supply transformed into 3 square waves with a 120° phase stagger by means of a electronic control board using FET. In order to reduce the energy requirement, various performance gain options were investigated by Istituto Giordano. These covered aspects of the electronic control device for the motor creating the DC supply. Tests were also carried out by modulating the frequency by new windings adapted for the supply voltage chosen (24 volts) and in looking at the reduction of the lubricating oil temperature. Additional work was carried out on the Indel B **DC motor** driven unit which was found to be not suitable at the voltages required. Comparisons were also made with a Stirling Compressor which in theory had a superior COP performance. This was found not to be so with the exception at low load when the Stirling compressor can reduce it's stroke to reflect the low load situation. The far greater cost, complexity and limited advantage of the Stirling compressor therefore excluded it from the project. Other compressor systems were also investigated such as non-hermetic and two stage compressors.

Work therefore concentrated on the initial compressor and optimizing the performance criterion of operating time on/off and the position of the temperature thermostat in relation to the evaporator in order to operate ***at*** the most effective COP at the operating temperatures required by the project i.e. 24 and **35°C.** The DC driven compressor was found to provide a increased COP value of 27°/0 between the temperatures 24-3 5*C by adopting a suitable operating strategy and managing in the requisite voltage band,

The evaporator design was also optimised to have an increased internal surface with minimum refrigerant requirements. Areas of further improvement on the evaporator design were identified by Instituto Giordano which could potentially bring increases in COP.

5.4 **Solar Cell and Control Circuitry**

A survey was carried out by Alten and CNR-Lamel to look at the most important producers of crystalline silicium photo voltaic solar modules so that the availability and prices associated could be computed for the model. The model predicted the overall energy requirements of the panel supply.

The electronic charging circuit design needed to be able to utilise the maximum energy from the photo voltaic cells to charge both the battery and run the compressor.

It also had to decide on the optimum operation to achieve the maximum efficiency of the total system. There still needed to be a suitable reserve backup when there was no solar energy. The overall priority was to maintain the internal temperature of the refrigerator for as long a period as possible yet operate in a way which could increase the COP of the heat pump system.

Due to the complexity of the switching logic, the electronic circuit was designed to utilise a programmable micro controller operating its own software to respond to the variation in energy demand between the cooling system and the battery. Prototypes were built and tested.

Solar panels were also designed assembled and rested which would be suitable for the potentially harsh environment that they will be installed in. A suitable support for the solar panels and the battery was also developed.

5.5 The Battery

The battery is traditionally a more troublesome aspect of the solar powered refrigerator in that they need regular maintenance and traditionally may be stolen for other uses. Lead acid batteries were initially chosen to be investigated by Oakdale Batteries Ltd as they have good deep discharge characteristics and for the capacity required offer the cheapest unit price.

Further research was required if the life of the battery was to withstand 1,000 cycles of deep discharge as well as having low water loss (low maintenance). A research programme was therefore instigated in conjunction with Oakdale Batteries and Anthem Laboratories Ltd. Part of this research programme was completed. The problem with the design of lead batteries is that to produce one which has good cycling characteristics requires a relatively high level of antimony but this also causes the increase gassing on charge during service life. The research target was to develop a battery with 0.5- 1°/0 antimony, yet, would still have minimal gassing requirements. Unfortunately at the mid point of the project Oakdale Batteries entered into receivership and were eventually bought by FIAMM of Italy (no longer an SME) which precluded them from the project.

It was not possible to locate a suitable SME battery manufacturer to replace Oakdale Batteries and therefore it was decided that research would continue to locate the most suitable battery or batteries that were commercially available yet which would still meet the performance criterion required for this market. This was carried out by NEB Associates with Anthem Laboratories. The contract with DGXII and work scope were therefore modified accordingly. The testing of the batteries was subcontracted to a suitable firm, Scientific Ltd.

An alternative SME partner, UA Extrusions Ltd were found, who had interests in the manufacture of refrigerator components and were prepared to be involved in the project.

5.6 Prototype Refrigerator Building and Testing

Once the various research tasks had been completed and the designs optimised and integrated, prototype refrigerators of 39 litre and potentially 85 litre (eventual] y 110 litre) were constructed and the 39 litre units tested both in the manufacturers test facilities, in Sicily under solar power and at Stuttgart University for a formal test procedure.

Quest Refrigeration with Bartoli (UK) Ltd managed this utilising the "super Insulation" into the casing of the refrigerator. Particular care was needed for the corner areas where "cold bridging" could occur. Battery boxes were also constructed which were suitable for the weight and for transport.

5.7 Final Testing

A conventional evaporator and a cool cell evaporator each of 39 litres capacity were tested independently at Stuttgart University FGHLK mbH with simulated energy inputs. The cool cell prototype refrigerator met the **temperature requirements** of the DIN 1S0 **7371** for the "Sub-Tropical Class" $T_{ambiant} = 38^0C$, $T_{cells} \subseteq 10°C$ during tests at Stuttgart University. Certification of this is available. Test indicate that the refrigerator will probably satisfy the "Topical Class"- $T_{ambiant} = 43°C$, $T_{cells} \subseteq 10^0C$. This test is continuing.

6. Results

6.1 The addition of vacuum panels into the sandwich cabinet construction of the refrigerator gave a mid-panel insulation factor which was approximately 10 times better than the conventional approach. Practical methods of introducing these panels into the structure were also managed with minimal corner losses.

6.2 The use of a static cool cell which can utilise the latent heat of freezing was shown to be beneficial in allowing the operation of the compressor to be managed to maximise the system COP, reducing the overall energy use and increasing the insulation effectiveness.

6.3 Two different substances were found to be successful as a cool cell medium.

6.4 A useful model was constructed which provides assistance in working with the different environmental conditions and physical parameters, providing the overall energy usage. This allowed the size of the solar cell and battery to be assessed. Field tests have confirmed the model approximations.

6.5 Cool cell designs for a 39 litre and 110 litre refrigerators were carried out.

6.6 Six prototypes of a cool cell refrigerator and six prototypes of a conventional evaporator design were constructed and tested in various locations. (all 39 litres)

6.7 The evaporator design was optimised to have an increased internal surface with minimum refrigerant requirements with new areas identified for COP improvement.

6.8 A DC driven compressor was found to provide a increased COP value of 27% between the temperatures 24-32°C by adopting a suitable operating strategy and managing in the requisite voltage band.

6.9 Development work was highlighted for improved performance by further design of the evaporator.

6.10 A programmable controller/charger has been developed which successfully manages the switching of the solar energy between the compressor and the battery depending upon the time of day and priorities set in the logic. Various alarms are also incorporated into the design allowing further critical inputs/outputs depending upon the market specification.

6.11 Solar cells have been selected which provide a best performance /price ratio and solar panel designs developed and prototypes made suitable for the adverse environmental conditions.

6.12 Batteries have been located and tested which provide a suitable operating performance in the high temperature environment. They allow suitable deep discharge for over 400 cycles with no maintenance. Tests are continuing.

6.13 A battery box has been designed and manufactured for the batteries.

6.14 A model of the different design options and prices for different markets was established showing major cost reductions.

6.15 Tests were carried out in the company laboratories, in Sicily and at University laboratories to validate the performance of the refrigerators.

7. Conclusions

7.1 This project has looked at the all the factors which are needed to optimise the performance of a solar powered refrigerator which could be used in the Developing countries.

7.2 The technologies when combined, have been successful in providing a cost effective solution, reducing the price of a typical high specification solar powered refrigerator by approximately one half thereby achieving the overall aim of the project.

7.3 The technologies such as cool cell, super insulation, programmable device and compressor/ heat pump improvements can also be combined into conventional AC driven systems.

7.4 The dynamic (pumped) design of cool cell is not practical for this size of refrigerator.

7.5 Extensive trials and detail design work will take place over the next year to perfect the technology and designs to provide the robust and reliable refrigerators for this potentially large but demanding market. Safety trials for the design and use of cool cell material will also need to be carried out.

7.6 The project has developed technologies and designs which should play an important role in bringing refrigerators to the developing countries at prices which are more relevant. Many variations are possible to provide a range of solutions for complex specifications to simple and cheaper refrigerators.

7.7 The commercial market is now becoming aware of this project and steps are being made to address professionally further development of the items researched, the market and the team performance in order to exploit the technologies on a world-wide basis.

8. Acknowledgements

This project would not have been carried out without the support of the European Commission and in particular DGXII Brite Euram CRAFT Technology Stimulation Programme. It has brought together the Research and Development skills and the complementary manufacturing skills of a team who together, now have the opportunity to create new markets for their products across the world whilst helping to minimise further pollution problems.

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