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PROTOTYPE THERMOELECTRIC AIR CONDITIONING OF A PASSENGER RAILWAY COACH

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Summary
A research and developpement program started in 1973 enabled a passenger railway coach to be equipped in 1977 with a thermoelectric air conditioning system. Description of the coach and the air conditioning system are given mathematical modeling and test bench performances are presented for the thermoelectric system. After three years in daily operation the experience acquired in presented.

1 - Reasearch and development program

Air Industrie having an important annual market in the air conditioning of railway coaches it was decided in 1973 to start with the Centre de Recherches de Pont à Mousson a research program concerning the air conditioning of the future for passenger railway coaches. An exhaustive study of all mechanical, physical and chemical processes showed that thermoelectricity comes out way ahead for several reasons of which the most important are :
- simplicity and reliability
- reversibility of system (can produce heat and cold)

1.1 Feasibility study

A feasibility study was undertaken in 1973 which consisted of :
- bibliographical study
- experimental measurements on a water-water system using 12 modules Ref. CP31-06 manufactured by Melcor Inc of Trenton New Jersey
- Thermal mathematical model of the small water-water unit which enabled using the above measurements to check the thermoeclectric material's properties
  s : Seebeck coefficient V/K
  : electircal resistivity
  k : thermal conductivity W/(m.K)
- thermal mathematical model of an air-air unit
- cost analysis

The conclusion of this study was that thermoelectric air conditioning for passenger railway coaches was definitely interesting under temperate climates such as the french climate where the range of temperatures over the year is between - 15°C and + 35°C.
It was estimated that it would take about 10 years to acquire complete mastership of the technique, it was hoped that over that lapse of time an improvement in thermoelectric materials would be significant, this has not turned out to be true.
The following research program was done in close collaboration with the french railways : Société Nationale des Chemins de Fer français (SNCF).

1.2 Research program

This program started in 1974 comprised the following aspects :
- thermal mathematical modelling of air-air units
- experimental work on the thermoelectric material
  . soldering of the thermoelectric material to heat conducting surfaces
  . measurement of the thermoelectric material's properties on samples used in the units.
- extensive theoretical and experimental work on heat exchangers optimised for the size of the thermoelectric material pieces.
- design and manufacture of a first laboratory prototype. The overall powers (heat, cold and electric) measured enabled us to test the model and then to optimise. Vibration and choc test indicated the necessity of certain structural aspects for the industrial unit.
- study of a railway coach with a thermoelectric air conditioning. This study which lasted through 1975 and 1976 was undertaken jointly with the SNCF. It was decided that a coach Corail VTU would be the basis for the study. The objective was to modify the least possible a standard coach body, and then assemble all its equipements and trimmings. These constraints limited the cooling power that could be installed to a value below that of the standard equipements. Nevertheless experience had to be acquired and the coach could be assigned to a part of the country where the maximum cooling power required is less than that of the standard equipment. A photograph of a Corail VTU coach, which looks just like thermoelectric, one is given in Fig. 1.

Fig. 1 Corail VTU passenger coach

A description of the final layout is given in paragraph 2.
- design and manufacture a first industrial unit.
  It was felt absolutely necessary to get an industrial unit in operation as soon as possible so as to be able to deal with the problems that would arise. The first industrial prototype was not of a design that would enable mass production. The system comprises 32 identical subunits. It was planned to substitute at regular intervals new subunits to allow a complete check of the subunits taken out and to also test improvements in subunit design.

The coach and the thermoelectric air conditioning were ready by late 1977.

2 - Description of the coach

The SNCF passenger coach is of the type Corail VTU[1,2] it seats 88 people in second class and is a saloon type coach with a glass partition in the middle of the coach on either side of the central isle. This divides the coach into non smoking and smoking areas.

2.1 Air circuits

The primary air is the air that goes through the thermoelectric units and that is either cooled or heated.

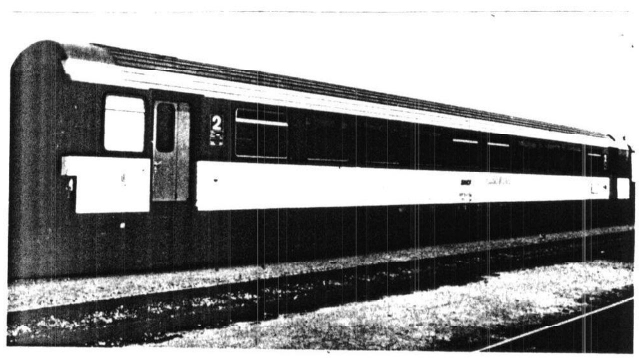

Fig. 1 Corail VTU passenger coach

The auxilary air is the outside air that cross-wise goes through the unit.
Air is taken from the coach at the foot of both sides of the glass partition hence from both areas. This air is mixed with fresh air, and become the primary air. It is filtered then cooled, heated or neither and then enters the coach through 4 ducts situated in the walls midway between the ends of the coach and the glass partition. This air prior to distribution into the coach in front of each window is mixed by induction with air inside the coach.
Air is extracted from both ends of the coach, a fan pushes it through the electric power converter so as to cool it. In winter the warm air from this converter is mixed with some of the auxilary air that goes through the thermoelectric unit.

2.2 Electric power supply
In the case of electric locomotives, the catenary power lines in Europe vary in voltage and in frequency. In France we have :
- 25000 V AC 50 Hz
- 1500 V DC

The electric locomotive operating in AC has a transformer that lowers the above voltage to 1500 V 50 Hz AC. When operating on a 1500 V DC catenary, this voltage remains unchanged. An electric cable runs along the train through each coach. Each coach has a high voltage converter that changes the 1500 V to suitable voltages. In the standard coach with a traditional compressor air conditioning system, the power outlets are 380 V 50 Hz 3 phase, and 24 V DC for the primary air fans lighting and the battery charger.
For the Peltier coach, the high voltage converter was modified to have 4 outlets. A schematic drawing of the power supply is given below in Fig. 2.

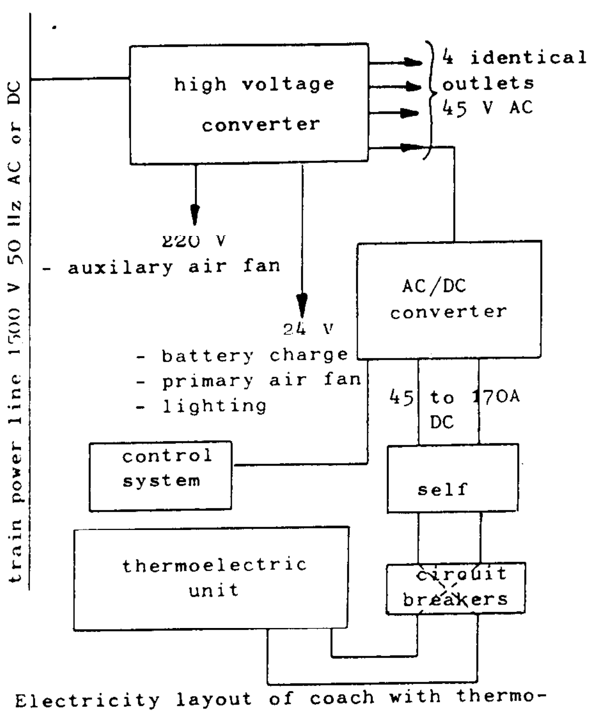

Fig. 2 Electricity layout of coach with thermoelectric air conditioning

There are 4 identical circuits from the high voltage converter to the 4 identical thermoelectric units. One of the these is described.
The AC/DC converter is controlled by the coach control system which has 2 output signals.
- an open or closed circuit which indicates if the DC current must be positive or negative (one corresponds to the heating mode, the other to the cooling mode).
- a voltage signal between 0 and 15 volts which determines the value of the DC current.

After the AC/DC converter there is a self to reduce the residual AC current which is a parasite to a value less than 1 % in power of that of the DC component. A double switching circuit breaker is located between the self and the thermoelectric unit. It has 3 operating positions :
- open circuit
- closed circuit with the current going to one end of the thermoelectric unit to cool the primary air.
- closed circuit with the current going to the other end of the thermoelectric unit to heat the primary air.

2.3 Thermoelectric Control System
The control has a primary function which is the temperature inside the coach and three auxilary functions which are : To reduce under certain circumtances the fresh air which is added to the primary air ; To dry out the primary air circuit of the unit before going from cooling to heating ; And defrosting the auxilary air circuit in winter.

2.3.1 Temperature
The controller measures several temperature of which
- temperature inside the coach
- temperature of air at exits of thermoelectric units
- temperature of outside air with the influence of the sun and the speed of the coach.

The inside air temperature is maintained at 22°C when the outside temperature is below 22°C. Then the inside temperature is slowly increased to reach 26°C when the outside temperature is 32°C.
These temperatures enable the controller to have a fast response and be able to anticipate tendancies. The output signal is proportionnal to the heat or cooling demand.
When going from one mode (heating or cooling) to the other, the current always becomes nil, then the switching circuit breaker is opened for a few minutes before closing again but such that the DC current is sent through the thermoelectric unit the other way. It takes the current between 5 and 10 seconds to reach it's maximum value.

2.3.2 Amount of fresh air
The air conditioning is designed for a flow of 20 m^3/h of fresh air per passenger. But when the outside air temperature is either below - 10°C or above 32°C it is reduced 50 %. The fresh air is also reduced at start-up in the same proportion so that the coach temperature has reached rapidly a comfortable value before passengers are admitted.

2.3.3 Drying of inside of unit (primary circuit)
When going from the cooling to the heating mode, as there is residual condensation in the thermoelectric unit ; If it is left in the unit it introduces too much moisture into the coach. So the drying consists of opening up a shutter at the exit of the thermoelectric unit, of putting the maximum heating on and to send out for 4 minutes the damp air into the atmosphere.

2.3.4 Defrosting
Frosting is the plague of all heat pumps. Calculations have shown[4] how thermoelectric heat pumps can frost up Initially the defrosting was operated when the outside temperature was below +10°C and that the heating had been on for a solid hour. It lasted 4 minutes. After the first winter defrosting was done automatically only once a day at the early morning start-up.
During the defrosting cycle the fans on the primary air are stopped, those on the auxilary air are operated as in heating mode and the electric current is maximum and in the direction to cool the primary

circuit, hence heat the outside to melt any frost.

3 - Description of the thermoelectric system

3.1 General description

The system is located under the floor of the coach Fig 3.

The caracteristics of the overall unit are :

- primary air flow rate 0.83 m^3/s
- auxilary air flow rate in Summer 6.12 m^3/s
- auxilary air flow rate in Winter 1.12 m^3/s
- cooling power is 17 kW under the following conditions :
  - . outside air 32°C and 60 % relative humidity
  - . inlet air temperature into the unit 28.8°C
  - . air temperature inside the coach : 26°C
- heating power is 26 kW under the following conditions :
  - . outside air 0°C
  - . inside air 22°C

The overall system consists of 4 identical units. All the air circuits are in parallal so the flow rates through each unit are a quarter of the above values. The coach being of the saloon type, each half of the coach corresponds to one half of the system as shown in Fig. 4.
A half of the system comprises 2 thermoelectric units, each one has its own primary air fan at the exit and one fan for the auxilary (outside) air. When the outside air temperature is below 10°C, the axial auxilary air fan operates as shown by the thin lined arrows, it corresponds to the heating mode. When the ouside air temperature is above 10°C the axial auxilary air fan turns the other way round and the air flows as shown by the thick lined arrows.

3.2 Description of a thermoelectric unit

A photograph of one unit with one shutter off is given in Fig. 5.

The overall dimensions of the unit are :

- length : 200 cm
- width : 45 cm
- height : 60 cm
- mass : 290 kg

Each unit contains 8 identical subunits which are in series on the primary air circuit.

3.3 Subunit

The subunit is factory assembled. It contains 288 cm^2

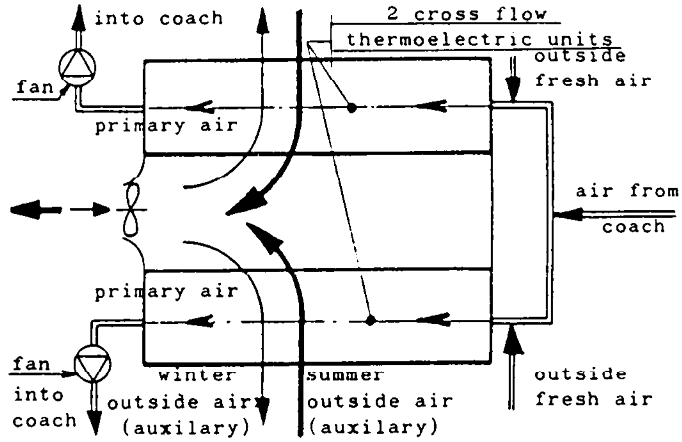

Fig.4 Schematic of thermoelectric system for half the coach

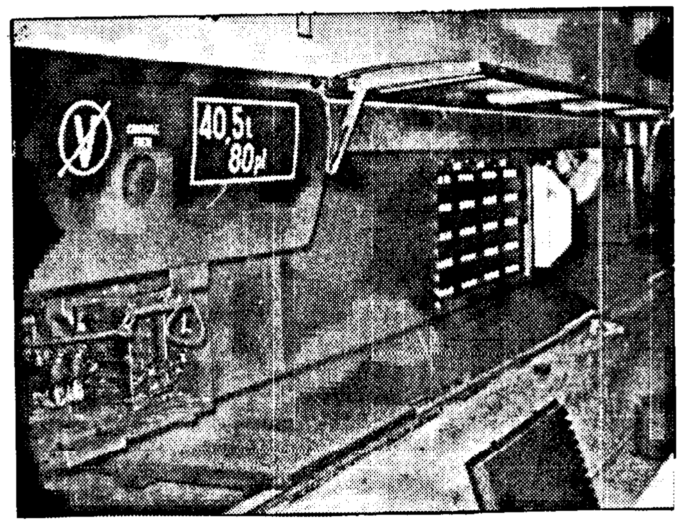

Fig. 5 Unit with one shutter off

of thermoelectric material of thickness 1.5 mm. The thermoelectric material is manufactured by Melcor of Trenton New jersey.
The heat exchangers consist of wavy fins of 0.3 mm thickness.

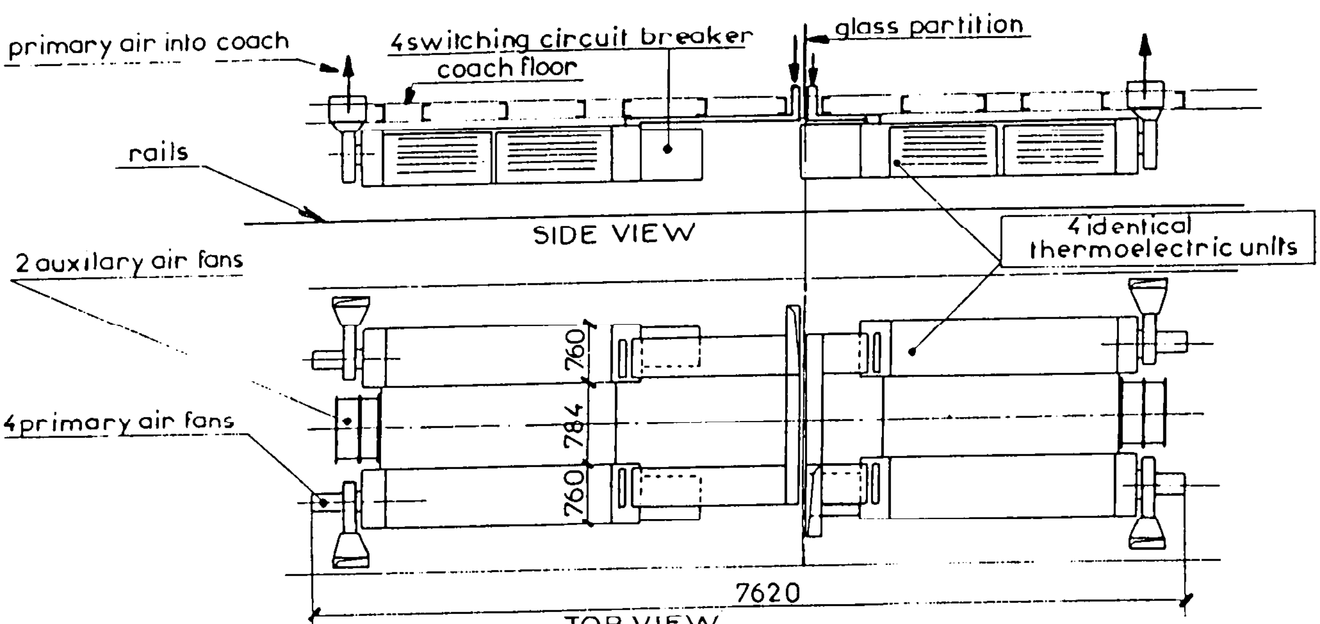

Fig3 General layout

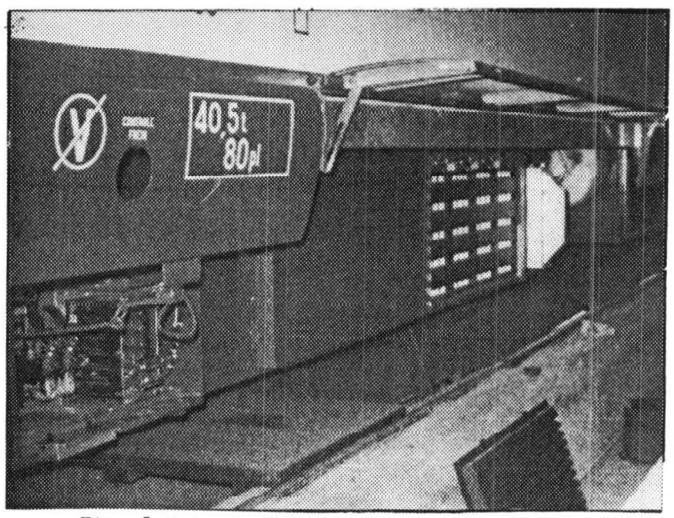

Fig. 5 Unit with one shutter off

The fin area per subunit on the primary air in 7.9 m^2 and on the auxilary air 7.2 m^2

4 - Mathematical modelling

4.1 Overall model

The modelling for cross flow thermoelectric air to air units has already been presented in detail [3,4]
The principal is to calculate the operating conditions of the two small heat exchangers associated to one piece of thermoelectric material. A schematic for 6 pieces (or groupes of pieces) of thermoelectric material is given in Fig. 6 below.

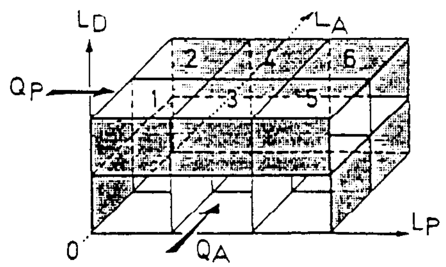

Fig. 6 Schematic of cross flow

The thermoelectric material situated between the 2 flows is not represented.
The calculation is done following the numbering of the columns, hence one knows the inlet conditions to the columns so one can calculate the exit conditions. The initial program was written in Fortran, recently the programs have been written in BASIC using a Hewlett Packard HP85 calculator.

4.2 Thermal and electrical resistances

It was found necessary to have models of heat and electrical conduction in solids. Large computer programs exist but for pratical reasons small models were written in BASIC to calculate conduction between the surface of the thermoelectric material and the base of the fins.
These calculations are a first approach, afterwards experimental mesurements are done to check the calculations. The results are satisfactory.

5 - Test bench performances

Experiments are done on the the components and on 4 subunits.

5.1 Thermal resistances

A small set up consisting of 2 X 3 heat exchangers shown in Fig. 7 below is used to measure thermal resistances. Copper rods are soldered to the aluminium finned heat exchangers that are copper plated at the interface with the rods so that a lead-tin solder can be used. Around each rod is placed a heating element of the type used in soldering irons. A thermocouple is place at the junction of each rod with its heat exchanger. Temperature measurements are made with a contact probe at various locations on the base of the heat exchanger and on the fins. Holes were made through certain fins to enable the measurement of fin temperatures. Many measurements are necessary so as to have averages that are significant. Results are obtained for the thermal resistance between the thermoelectric material and the base of the fins and for the converction coefficient of the fins as a function of air velocity. Pressure drops are also measured.
The above measurements are used in the thermal models

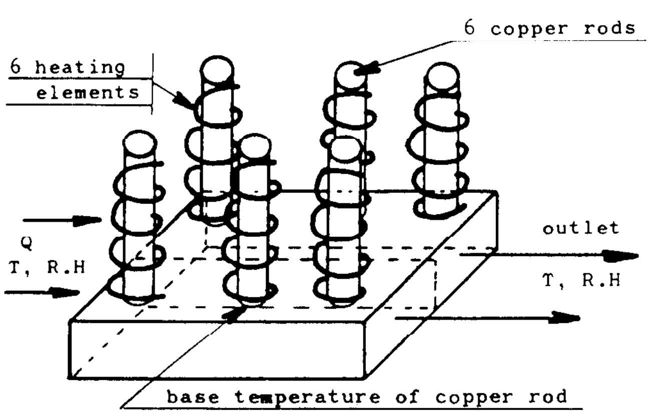

Fig. 7 Thermal resistances set up

5.2 Measurements on a unit

A test bench with two closed air circuits was designed built and tested for systems of 4 subunits.
The circuits characteristics are :

- primary circuit
  - . air flow rate up to 950 m^3/H (0.26 m^3/s)
  - . temperature range -5°C to 35°C
  - . heating power 2,5 kW
  - . cooling power 10 kW
  - . humidification 4 kg/h
- auxilary circuit
  - . air flow 3000 m^3/H (m^3/s)
  - . temperature range - 10°C to + 40°C
  - . heating power 2,5 kW
  - . cooling power 15 kW

An example of such measurements are given in Fig. 8.

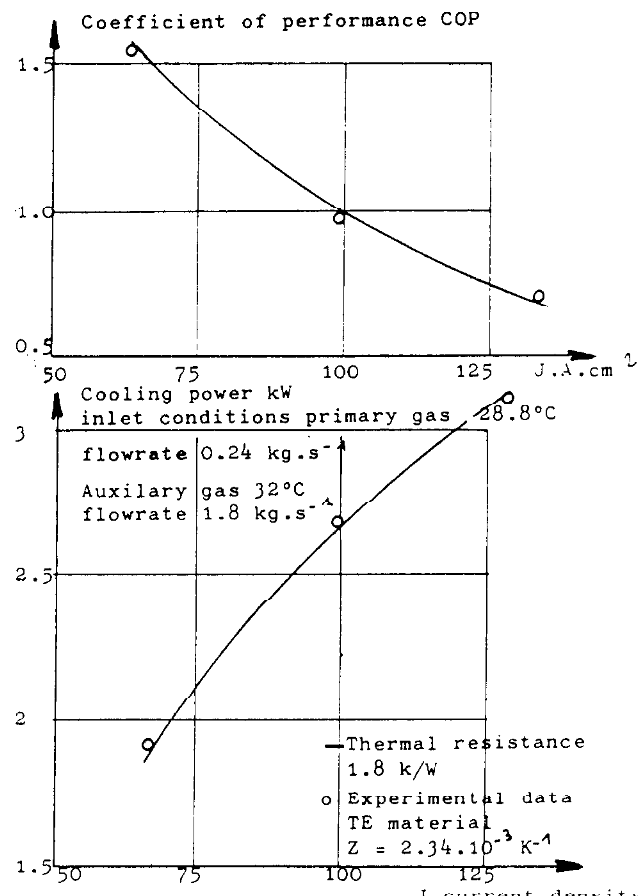

Fig. 8 Performance of 4 subunits A/cm ^{2}

The thermal model is ajusted using the overall measurements from the 4 units. One subunit is instrumented in its center : thermocouples measure the base

temperature and fin temperatures of a hot and a cold heat exchanger. The measurements are compared with those of the model at that given location.
It was found that the test bench did not enable us to have saturated air at the inlet of the primary air, so we were unable to operate under conditions corresponding to the last 2 or 3 subunits in a unit containing 8 subunits in series on the primary air.

6 - Thermal measurements on the coach

Thermal measurements were done with the coach stopped and with the coach rolling at 160 km/h.

6.1 Heating tests

The coldest outside temperture during the tests was - 1.5°C. The heating power was 29 kW with a COP at the entrance of the thermoelectric unit of 1.15.
The heating measurements made confirmed the model.

6.2 Cooling tests

An initial test were done in an oven where the outside temperature was 38°C and the relative humidity above normal climatic conditions. The measured cooling powers were greater than expected. Later tests were done with normal humidity conditions. The results were 10 % below our predictions.
The cooling power being composed of two parts :
- power to drop the air temperature (sensible heat)
- power to condense the humidity (latent heat)

It was found that the first part, at maximum electrical power, is constant and equal to 12 kW.
The second part increases with the inlet relative humidity. The measured exit relative humidities, were of 95 %.

6.3 Measurements with the coach rolling

A centralised measuring equipment is installed in the coach that consists of a 32 channel tape recorder.
For thermal measurements the cycle time was every minute, but for systematic checking a 5 minute cycle was sufficient.
Among the measurements made were :
- electrical intensity and voltage on each unit.
- signal of heating or cooling mode
- inside air temperature
- outside air temperature

Attemps to do a heat balance showed that the coach was always in a transition mode due to the thermal inertia of the coach itself. This due to the fact that the coach goes through in rapid succession different landscapes. The system served essentially to check the operating conditions.

7 - Operating experience

The following various aspects are examined

7.1 Failures

Over a 3 and a half year period there was no failure of the thermoelectric units. This confirmed the ruggedness of the design, but stoppages of the air conditioning did occur.
They were due to the following :
- high tension converter
  the converter used is a modified standard converter. For the first several months there were several breakdowns of the electrical power system, then no more incidents occured
- AC/DC converter
  this is a prototype build for this specific application. The electronic control cards caused a certain number of stoppages :
  - electrical connections
    It was found necessary on some test subunits that replaced the initial ones to reinforce mechanically.
    the electrical connections between the subunits.
  - auxilary air fan
    Twice one of the 2 axial fans broke doun, the motor had burnt out. It is believed that an outside object hit the fan blades, even though they are protected by a grating, but no marks were found on the blades.
  - shutter on primary circuit.
    One of the 4 shutters that open up during the drying cycle before going into the heating mode had an axel jam. It was changed and all the shutters have operated normally since.

To conclude there was not a single failure of the thermoelectric units. Putting aside the start up problem of the high tension converter. All the incidents except 3 mechanical ones (fan motor and shutter axel) were due to the prototype AC/DC converter.

7.2 Temperature control

Recordings made with the centralised tape recording system showed a remarkable stability within plus or minus 0.2°C. This is due to the excellent control system with a proportinal signal for the AC/DC converter that defines the electrical intensity through the thermoelectric units.

7.3 Inversion

The sequence from cooling to heating mode contained a 4 minute drying cycle during which the air exiting from the 4 thermoelectric units is sent out into the atmosphere.
For 1 year the drying cycle was operated each time the control system requested heating after operation in the cooling mode. It was then decided to only operate the drying cycle at the start up every morning when the electrical current came on. No excessive humidity was observed when the system went from the cooling mode to the heating mode. The system has operated this way for the past 2 and a half years.
It is felt that in more humid hot climates the drying cycle would be necessary each time the system goes from the cooling to the heating mode.

7.4 Defrosting

When the coach is operating non stop in the heating mode for 12 hours, a defrosting cycle is operated. After 1 year the defrosting cycle was stopped and since there has been no frosting incident. The coach was observed closely during some bad snow stroms where the underside of the coach was one mass of ice and snow. The temperature inside the coach remained normal and after a 5 hour journey the sides of the coach were raised and one could see that though 50 % of the side of each unit was blocked the unit was able to operate sufficiently well.

7.5 Performance stability of thermoelectric subunits

The most important quality control criteria is the electrical resistivity of each subunit. The measurement is delicate because very sensitive to ambiant temperature as each subunit consists of approximately 100 thermocouple juctions in series. A temperature correction factor was used to compare all results at 27°C. The best correction factor was found to be of + 0.33 % per degree C, the resistance increases with temperature. Every month or two measurements were done on each subunit, and each unit of 8 subunits.
After temperature correction, variations of plus or minus 1 % of the electrical resistance were recorded, so a sliding average using the last 3 measurements enables one to detect trends when they exceeded plus or minus 0.5 %.
Subunits that have been in daily operation for over a year and a half, have electrical resistances that vary within a margin $\pm$ 0.5 % with no specific trend to increase.

Some subunits where changed so as to completily check the one taken out. The Seebeck coefficient of pieces of thermoelectric material that have been in daily operation for over 3 years is unchanged within the precision of the measurement estimated to be within ± 3 %. Measurements were made on numerous pieces that had been initially individually checked, no decrease in the averages was observed.
This industrial experience, over a period of over 3 years shows that the technology has been mastered.

8 - Conclusions

A standard passenger railway coach has been equipped with a thermoelectric air conditioning system. It has been operated daily by the SNCF on the French railways.
The various objectives of the trial have ben met. The reliability of the thermoelectric units has been 100 % over the 3 and a half year period.
A complete system has been operated successfully and thermoelectric air condtioning has proved to be particularly advantageous where rapid variations in thermal power are required because the level of cooling power or heating power can be constantly adapted to the thermal requirements of the coach by the temperature controller which changes the DC current into the thermoelectric system.
Operation from the cooling mode to the heating mode depending on the climate requires a drying out cycle to eliminate condensation.
A defrosting cycle was tested but it was not found necessary with the french climate.

The experience acquired will lead to the design of thermoelectric units, which can be manufactured on an industrial scale.
Future developpement will require the design of a complete system with its high voltage input power supply. It is expected that the input high voltage electrcal power and the overall mass can then be reduced.
Improvement in the thermoelectric material characteristics will obviously be extremely favourable

Reference :

1. BERNARD J.P. ; PUJOL-SOULET L. ; WILLAIME J. Les nouvelles voitures à compartiments VU75 de la S.N.C.F. Revue Générale des Chemins de fer. Février Avril 1977

2. STERNAT P.. Le Conditionnement d'air dés nouvelles voitures à compartiments de la SNCF. Revue Générale du froid Nov. 1981 pp 573-583

3. STOCKHOLM J.G. ; DESPRES J.P. Large scale thermoelectric cooling. 2nd International Conference on thermoelectric Energy Conversion. The University Texas at Arlington March. 1978 IEEE Catalog N° 78 CH 1313-6 REG 5.

4. STOCKHOLM J.G. ; BUFFET J.P. Large gas to gas thermoelectric heat pumps 3rd International Conference on thermoelectric energy conversion. The University of Texas at Arlington March. 1980 IEEE Catalog N° 80 CH 1546-1 REG 5.