Commission of the European Communities

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DEVELOPMENT OF ENERGY EFFICIENT ELECTRICAL HOUSEHOLD APPLIANCES

Part One: REFRIGERATORS

Report

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Part One: REFRIGERATORS

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FINAL REPORT

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OBJECTIVE

The objective of the part of the project described in this report was to develop and build a prototype of a low energy refrigerator, consuming only about one fifth of the electricity consumed by a typical 1975 refrigerator.

SUMMARY

This final report is part one out of three parts describing a project on efficient household appliances.

Earlier analyses indicated significant potentials for saving electricity used for refrigeration purposes. The work reported here was undertaken to verify those conservation potentials by designing and building low energy refrigerator prototypes. The project was carried out in cooperation with the refrigerator manufacturer Brdr. Gram. Improved compressors were provided by the compressor manufacturer Danfoss.

A 200 liter low energy refrigerator with no freezer compartment was designed. A few prototype cabinets were built with better insulation than usually. A compressor with improved performance was used in the refrigeration system installed in the cabinets. Furthermore, the evaporator and condensor were improved. The system is automatically defrosting.

Electricity consumption for the low energy refrigerator was found to be 102 kWh/year under standard test conditions. This is about 20 percent of what a typical 1975-refrigerator of same size consumes, and 40 percent of what one of the best on the market consumes. We have thus reached our target. However, experimental tests indicated that the insulation standard was better than anticipated, while the refrigeration system was performing below the expected. We conclude that further reduction in electricity consumption is possible through a better adapted compressor, better control systems etc. Litterature studies and a few preliminary experiments were carried out in order to evaluate the possibilities for solving these problems. No ideal solutions were found, but the work continues at Physics Laboratory III.

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INTRODUCTION

The background for the project is an energy analysis carried out in 1974 to 1979, investigating future energy options for Denmark, (1,2,3). This analysis included theoretical studies of how energy efficient the major household appliances could be designed. On the average it was found that their annual electricity consumption could be reduced through technical measures to about one third of what the 1975-stock of appliances consumed. For some appliances like refrigerators and freezers the potential savings were larger, and for others like cookers they were smaller.

Later studies confirmed these findings and indicated a tendency among manufacturers to design more energy efficient models (4,5,6).

It seemed natural to supplement these theoretical studies with some experimental investigations, including the building of prototypes of appliances.

The purpose of the project was to construct and test such prototypes, designed for actual production. Three types of appliances were chosen because of their large distribution and importance to many European households. The three are: refrigerator, cooking devices and washing machine. The project was started September 1981 to run until April 1984, but was by a new contract extended till August 1984.

This report only covers the part of the work carried out concerning the refrigerator, but similar reports are made for the two other parts of the project. The progress of the work has steadily been reported in five progress reports to the Commission of the European Communities. This report is part one of the final report summing up the former progress reports, plus the latest period of progress, which has not previously been reported. Furthermore, this report also includes the result of our work during the extension of the contract.

Targets for electricity savings

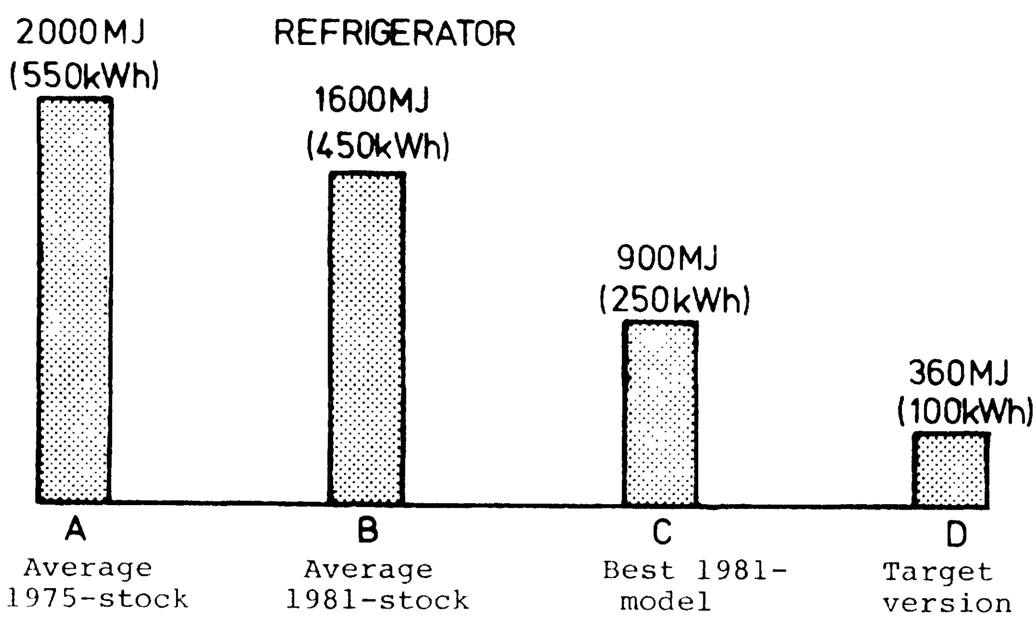
The target for the project was to reduce electricity consumption for the refrigerator, as shown on figure 1, without significantly affecting the service and comfort we get from using the refrigerator.

The graph also shows how much improvement has already been achieved by some manufacturers. In designing the improved 1981-models the manufacturers have focused on the refrigeration system and achieved a <u>55% reduction</u> in electricity consumption compared to the 1975-stock.

These improvements made it more difficult for us to reach our original target in <u>relative</u> terms. In <u>absolute</u> terms, however, it was more easy for us to reach our target, and less radical design changes were required than was proposed in the first theoretical work (1,2).

<u>Cooperators</u>

In the project we have been cooperating with two private companies, 1) the compressor manufacturer Danfoss A/S, Nordborg, Denmark, which has supplied the compressor unit and control systems and 2) the refrigerator manufacturer Brdr. Gram A/S, Vojens, Denmark, who provided know-how concerning the design of the refrigerator cabinet and installed the insulation material



<u>Figure 1</u>. Annual electricity consumption for different versions of a 200 liter refrigerator, all in "normal" use.

and the cooling system. Futhermore, we have been in close contact with the Danish Government Home Economic Council, which is the official institute in Denmark for testing appliances and other households consumer goods.

TARGET FOR THE DESIGN OF THE REFRIGERATOR

First step in the project was a contact with the company Brdr. Gram A/S. Formalities of cooperation were negotiated and agreed upon. Basic specifications of a prototype refrigerator were established. A preliminary time schedule was set up, and activities were distributed. A meeting was held at Danfoss A/S, and the company's Applications Department undertook the task of supplying a high efficiency compressor, that met with our requirements.

We agreed on the following specifications for the refrigerator :

1. Size, performance, comfort.
   - The refrigerator must meet with international standards for temperature distribution, and cooling capacity.
   - External size must be standard as far as width is concerned, that is 6o cm.
   - Comfort and operation must not be inferior to that of a normal refrigerator.

2. Energy consumption.
   - We aimed at building a low energy refrigerator (LER) consuming only 0.27 kWh per day (100 kWh per year) in "normal" use. This was assumed to be equivalent to a consumption of 0.31 kWh per day, at standard tests with 25°C ambient temperature, 5°C inner temperature, and no user load, that is, no door-openings and no exchange of contents. As the prototype was designed to have a total inner volume of 209 liters, this standard consumption equals 1,5 Wh per liter of net volume per day.
   - We chose to compare with the 215 l refrigerator (K215) from the company Gram, which at that time was declared to have an electricity consumption of 0.67 kWh per day or 245 kWh per year, according to standard tests.

3. Technology.

- -Production af the refrigerator must not require new technologies or new techniques in the tooling.
- -Production must not increase environmental hazards, compared with the traditional production of refrigerators.

It is important to note that refrigerators usually are tested at conditions according to standard tests with 25^{o}C ambient temperature, 5^{o}C inside and no user-load, whereas the target for the energy consumption of the refrigerator is set according to normal use. Kitchen temperature will be lower than 25^{o}C, which both 1) reduces heat load and 2) improves the COP. On the other hand, in normal use the door is opened, and food with room temperature or even warmer is put into the refrigerator. The heat load derived from the transmission of heat through the walls, however, makes up by far the greatest part of the total heat load, and hence the consumption in normal use was expected to be less than the consumption according to standard test conditions.

The savings in the amount of electricity consumed in normal use was anticipated to be around 350 kWh per year, compared to average stock in 1981 and 150 kWh per year when compared to the best on the market in the same year.

The K 215 refrigerator from Gram was used as a reference. It has a 215 liters of total inner volume and consumes around 250 kWh of electricty per year under standard test conditions. The outer dimensions are: height 106 cm, width 55 cm (which is 5 cm less than the normal standard) and depth 63 cm. It contains no freezer compartment (most Danish households have a freezer as a separate unit), and the defrosting is achieved automatically by letting the evaporator temperature rise above 0^{o}C before starting the compressor. The insulation layer is approximately 3 cm thick and is made up of polyurethane foam. The compressor used is the TL2.5A from Danfoss.

THE DESIGN OF THE PROTOTYPE

In the design of the LER prototype our efforts were directed towards two main areas of improvements, namely the insulation standard and the cooling system. These two ways of improving the performance of the refrigerator are, however, not independent of each other, as for instance improving the insulation standard will require the use of a smaller compressor, and smaller compressors tend to be less efficient. We decided to attempt reaching our target by improving both the insulation standard and the cooling system.

New inner cabinet

According to (7) energy consumption as a function of insulation thickness follows the pattern shown in Fig. 2. Energy consumption continues to decline as thickness increases. Comfort of use is, however, significantly affected when thickness grows beyond 7-8 cm, because our specifications ties us to standard outer width. We therefore settled at 7 cm insulation as a compromise which could enable us to reach our target of energy efficiency.

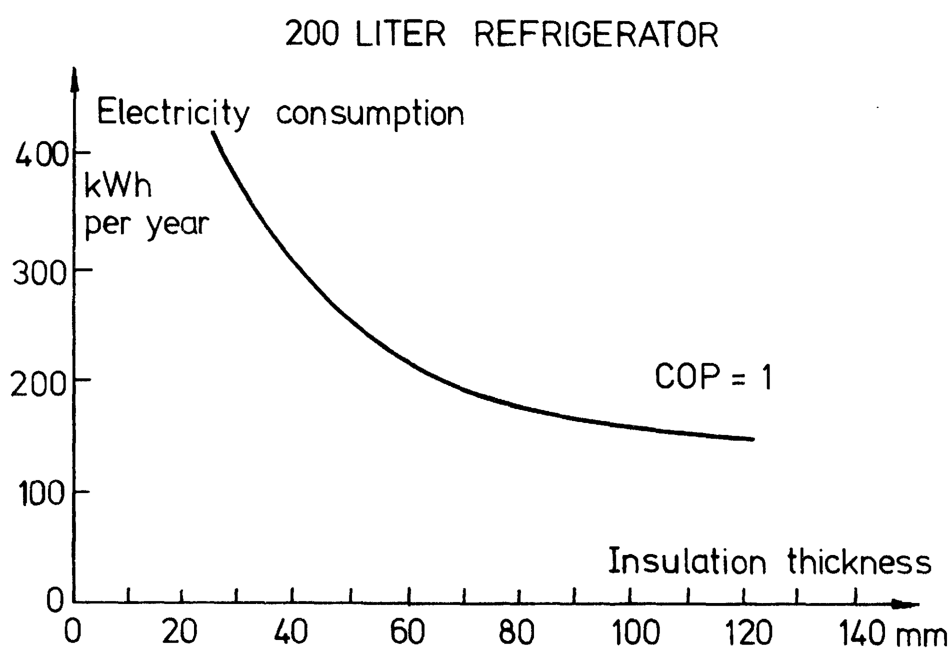


Figure 2. Annual electricity consumption versus insulation thickness calculated for a 2oo liter refrigerator when standard width and depth are maintained, and when COP is kept constant at 1.0.. Thermal conductivity coefficient of the insulation materials is assumed to be 0.029 W/m·°C.

Design of the LER prototype has been done at our laboratory, as well as construction of the inner box and a special tool which supports the inner box during expansion of the insulation foam. Only a few inner boxes are made for the prototypes and for this small scale producton the boxes were made of fibre glass reinforced plastic. The main inner and outer dimensions of the LER prototypes are shown on figure 3. Net inner volume of LER is about 200 liter.

The outer steelbox used is that of a Gram K285 with its door built with vertical "fins" or "shoulders", which are used for containing special storage boxes, see Fig. 3. On the outside of this K285 door is, however, added extra 4 cm of insulation. This was a convenient way of making doors for the prototypes, but it adds to the depth of the refrigerator compared to standard depth. LER occupies therefore slightly more floorspace.

The inside width and depth are both reduced by approximately 4 cm when compared to our reference refrigerator K215, which has a net inner volume of 206 litres. The 200 litre in LER is reached by making the interior about 12 cm higher than in K215. See more about net volume under test results, page 24.

It is assumed that the narrow air gap between the "shoulders" on the door, see Fig. 3, and the fold in the LER cabinet, acts as a kind of seal and reduces the heat transmission from cold bridges around the gasket. The gasket is of the normal magnetic type, also used in K215.

In fact, the insulation layer is not 7 cm thick all over, as its thickness is reduced towards the aperture. The average thickness of the insulation in the LER is about 6.5 cm.

Increasing the insulation layer from 3 cm to 7 cm was expected to reduce the total heat load, Q, to approximately half, given that the gasket and other coldbridges around the door are unchanged. The heat load from heat transmission was for the LER calculated to be 24 W at standard-test conditions.

The workshop at our laboratory built seven inner boxes for LER prototype of glass fiber reinforced plastic, see Fig. 5, using a heavy duty tool, Fig. 4, as a mould when boxes were laid up. Afterwards this tool was modified by simple means so that it could be used as the internal support against the pressure created during expansion of the polyurethane foam used as insulation.

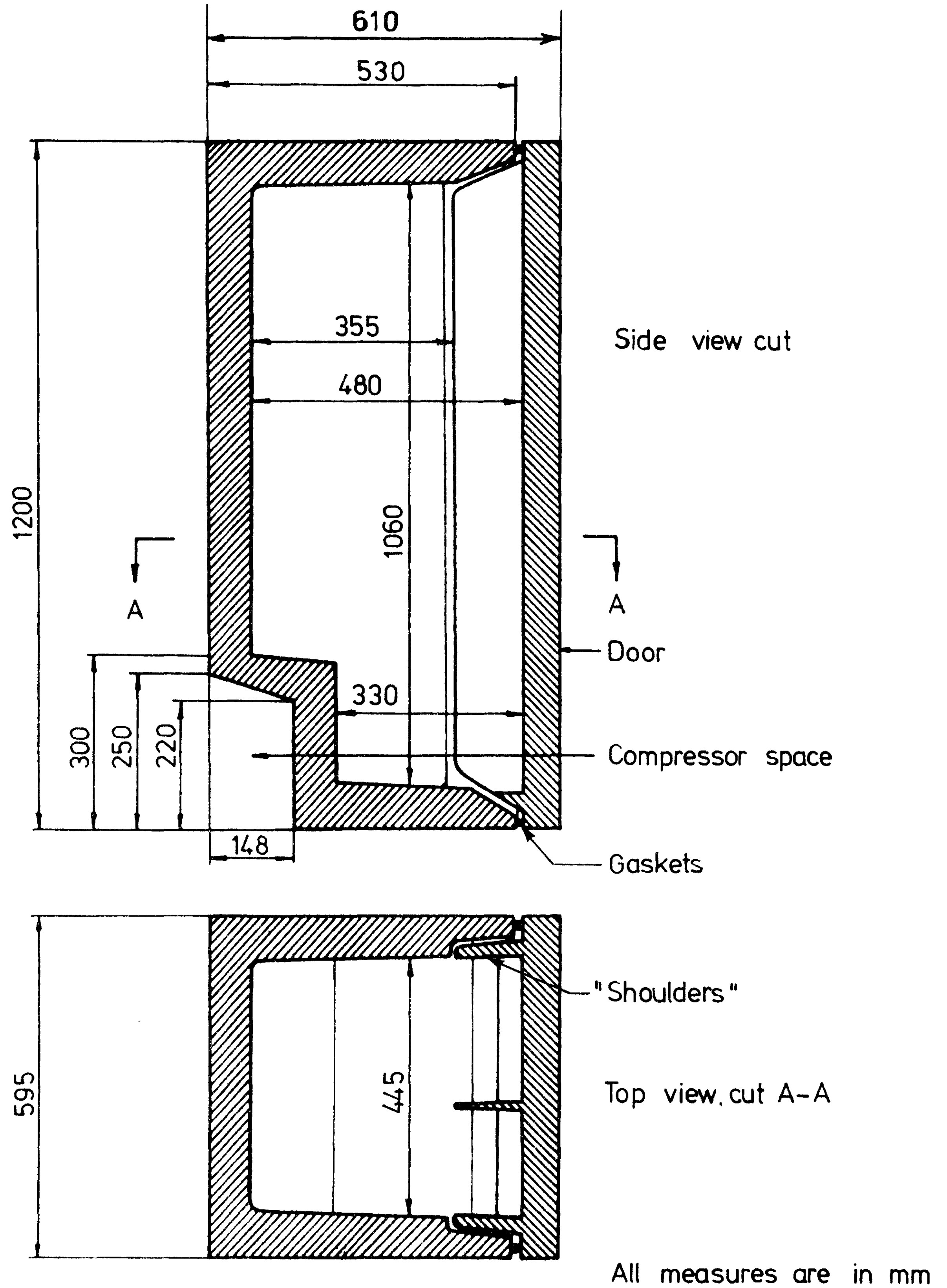


Figure 3. Design of the 200 liter cabinet for a low energy refrigerator, LER, with approximately 65 mm polyurethane foam insulation.

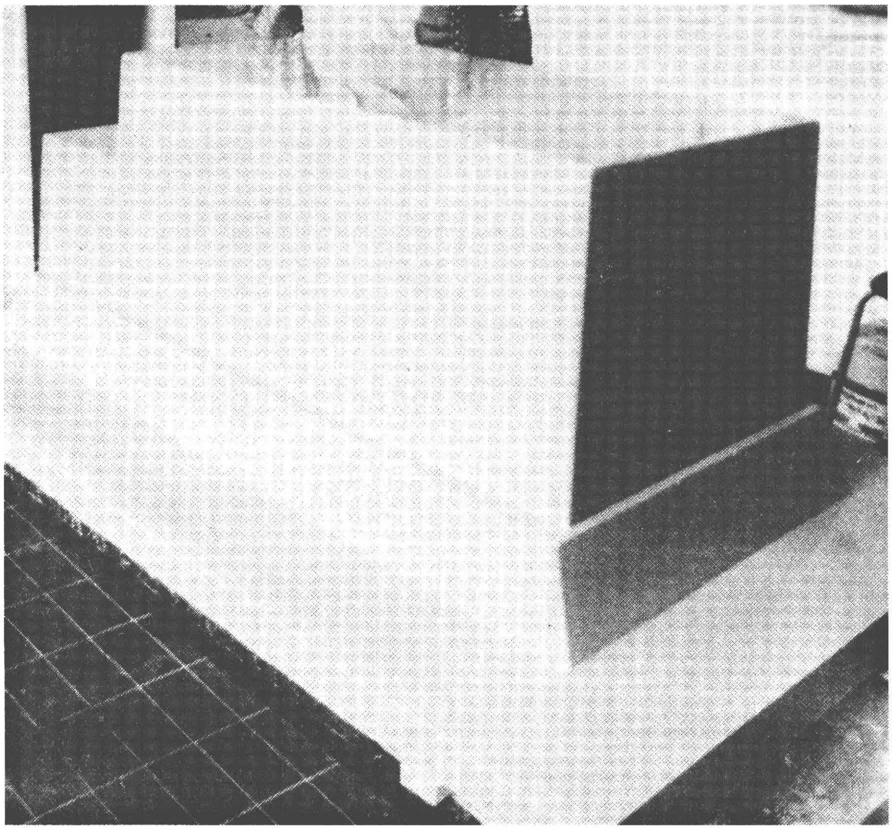


Figure 4. The heavy duty wooden tool, used as a mould for the inner box of the LER, and after some modificationalso used as internal support during the foam insulation process.

After having built the plastic inner boxes the next stages took place at Gram's factory in Vojens. The seven inner boxes were installed into the external steel cabinets of a standard K285 refrigerator. Next the insulating polyurethane foam was expanded in the cavity between inner and outer box creating a rather high pressure. As mentioned the mould used for making the inner boxes also served as a support for the inner box during the foam expansion. The foaming process usually requires some test fillings before a correct specific density of the foam is achieved. Hence the expert foresaw that most of the seven cabinets would be lost, but partly through good luck all seven cabinets were insulated satisfactorily.

Three refrigerator cabinets were stored away and four went on in the assembling process.

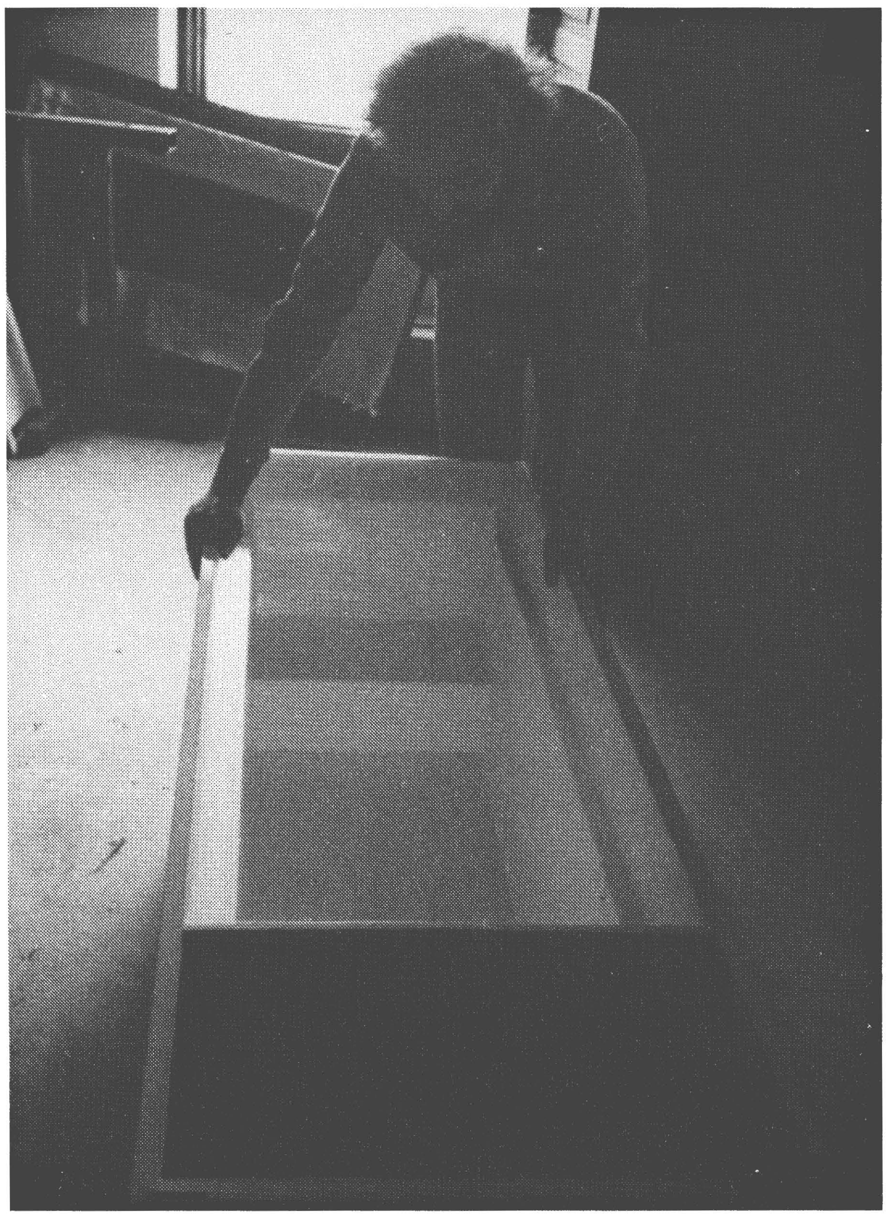


Figure 5. A new internal glass fiber reinforced plastic box for a LER prototype is being installed in a standard external steel cabinet, originally used for a 285 liter refrigerator.

Figure 6. Interiour of the low energy refrigerator, LER. Standard storage boxes from Gram are used in the door. Net inner volume is 200 liter.

Improving the compressor

For the refrigeration system required to keep the LER cabinet cooled we planned to increase the COP (Coefficient Of Performance). COP is here defined as the heat removed from the refrigerator divided by the electricity needed to do this. (If the system is used as a heat pump, the COP-value is 1.0 higher). Todays refrigerators - even the best - are typically run by a system with a COP less than 1.0. We aimed at a COP in the range between 1.5 and 2.0. The measures included changes in the heat exchangers, that is, the evaporator and the condensor, and in the compressor.

When the heat load on the refrigeration system is lowered through better insulation, a lower capacity of the compressor is needed. This, however, brings about a problem, as the smallest hermetic compressors are less efficient than the larger compressors, and thus the positive effect of improving the insulation-standard is to some extent being lost.

In order to overcome this problem two modified compressors were designed and built by the compressor manufacturer Danfoss. Test results pointed towards an improvement of the coefficient of performance, COP, of 33 percent, or a reduction in energy consumption per cooling capacity around 25 percent for a standard cooling process. This was obtained by mechanical and electrical improvements.

The compressor pump was provided with a newly developed "Direct Intake System" i.e. a system in which the suction gas is directed to the cylinder intake. In this way the suction gas arrives at the cylinder with higher density because the usual heat exchange with the motor and other warmer parts is reduced.

The motor system was also changed. In fractional horse power compressors the most common motor system is what in the trade is known as RSIR (Resistance Start Induction Run). The motor used in the special compressors was optimized for the purpose (as regards torques and efficiency). The motor system used was "Resistance Start Capacitor Run". In other words, during operation the auxiliary winding is active and coupled in series with a run capacitor.

Figure 7 shows how well the improved version of the TL2A compressor is performing. The original performance of the TL2A is shown on Figure 8 for comparative purposes.

It is important to note that the two graphs represent the performance of the compressors at steady state with no subcooling of the liquid refrigerant from the condenser. In actual operation there will be a loss deriving from starting up the motor and it is questionable whether the liquid refrigerant from the condensor is actually fully condensed at arriving to the evaporator. Furthermore the whole compressor unit will not be at steady state temperature in actual operation. This influences the viscosity of the oil and how much the gas is heated once it enters the compressor.

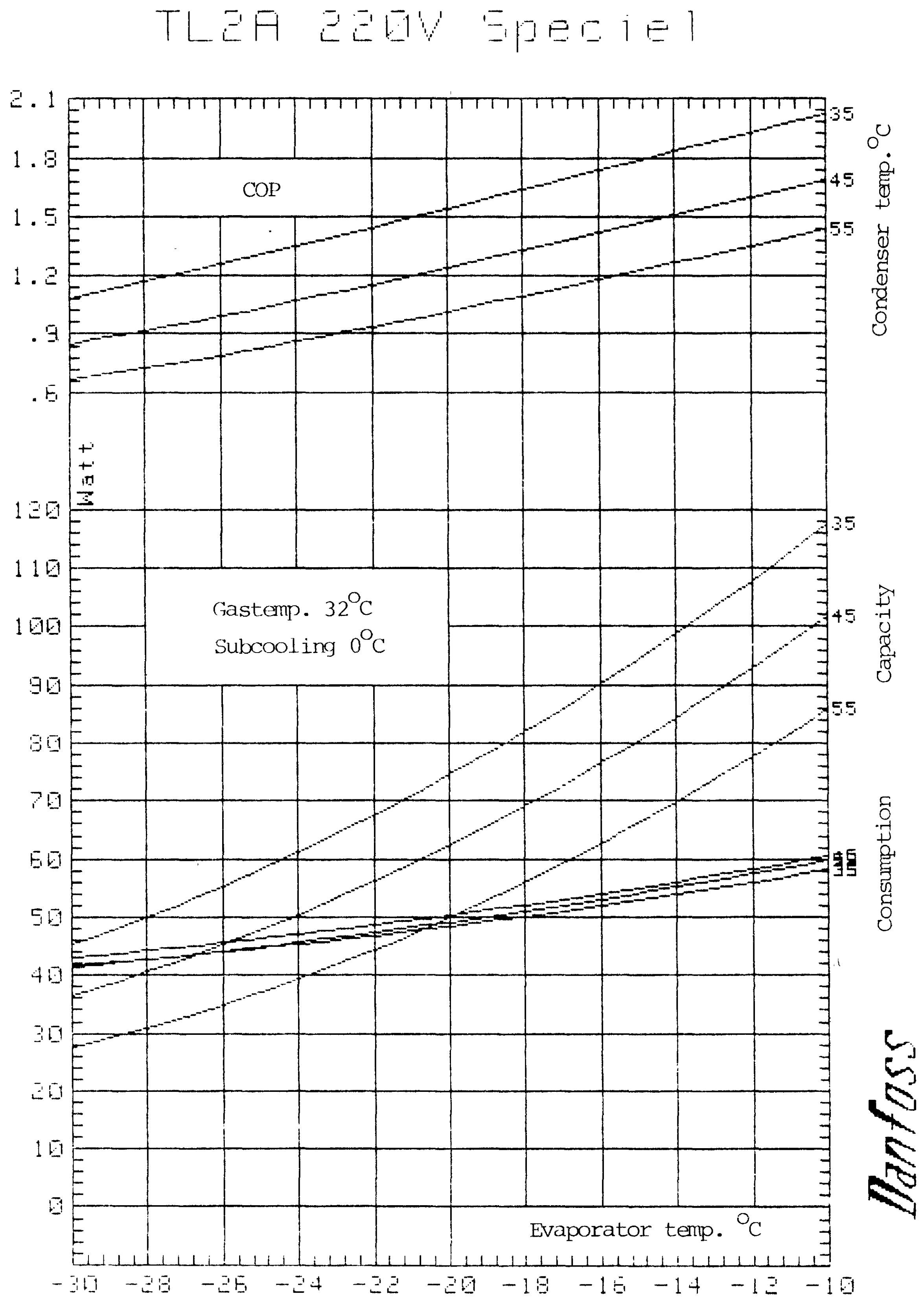


Figure 7. Performance of the improved version of the TL2A compressor at various temperatures of the condenser and the evaporator. This compressor version is used in the LER2 and LER3 refrigerators.

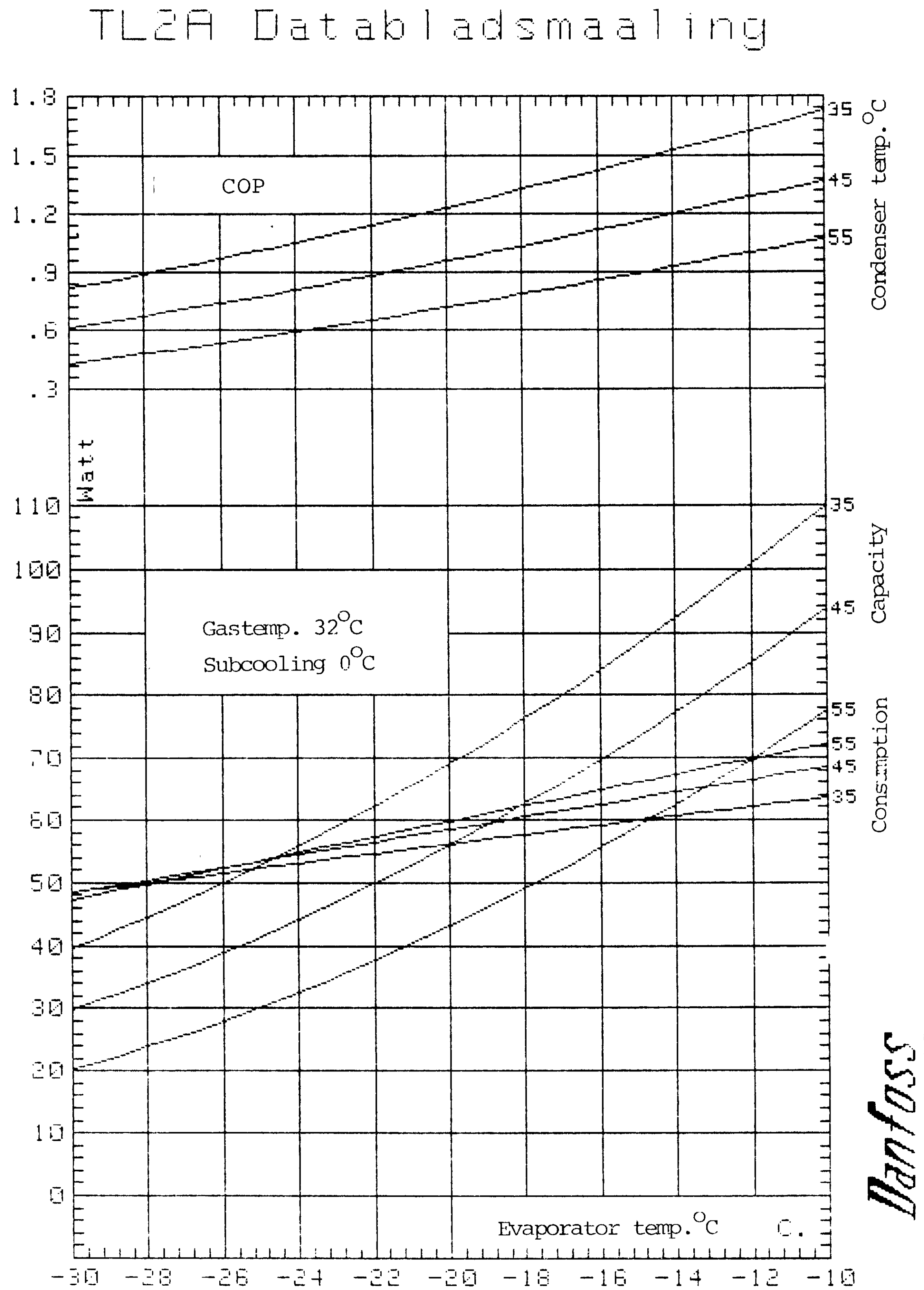


Figure 8. Performance of the original TL2A compressor at various temperatures of the condensor and the evaporator. This compressor is used in the LER1 refrigerator.

Better and larger heat exchangers

In order to increase the COP of the LER, compared to that of the K215, we planned to increase the evaporation temperature and reduce the condensor temperature, hereby improving the working conditions for the compressor.

If the surface area of the evaporator is increased, the refrigerator can be cooled with a higher evaporator temperature. Today an evaporation temperature of -20°C is not unusual in a refrigerator where the end use requirement is +5°C. If we, as here, exclude a freezer compartment, an evaporator with a temperature around zero can manage the cooling. Futhermore it is important to note that when the heat load on the refrigeration system is lowered through better insulation, a lower capacity of the compressor is needed and the sizes of the heat exchangers relative to the compressor are automatically increased.

The evaporator chosen for the LER prototype was 70 percent larger than that of the reference refrigerator K215. For LER the surface area is 0.24 m^2 at each side of the evaporator. Due to its larger size the evaporator covers more of the back wall inside the cabinet. This might reduce the flow of air to the back part of the evaporator and thus reduce its efficiency. This problem has, however, not been investigated.

As for the condensor, the size chosen for LER was about that in the reference refrigerator, but the type of radiator grid was better designed and was also heavier, which means that the heat capacity was increased. Both heat exchangers were standard heat exchangers from the refrigerator manufacturer Zanussi.

The refrigeration system

Figure 9 shows a diagram of the refrigeration system employing R12 as refrigerant. The cooling system is quite ordinary and similar to that used for the K215. The evaporator is defrosted automatically during standstill by letting the temperature of the evaporator rise above zero. The defrosting water is lead out of the cabinet through a tube and evaporates in a small open box by means of the heat from the compressor. The use of a separate insulated heat exchanger transfering heat from the condensor tube to the evaporator tube makes sure that no liquid is sucked into the compressor and hereby damaging it.

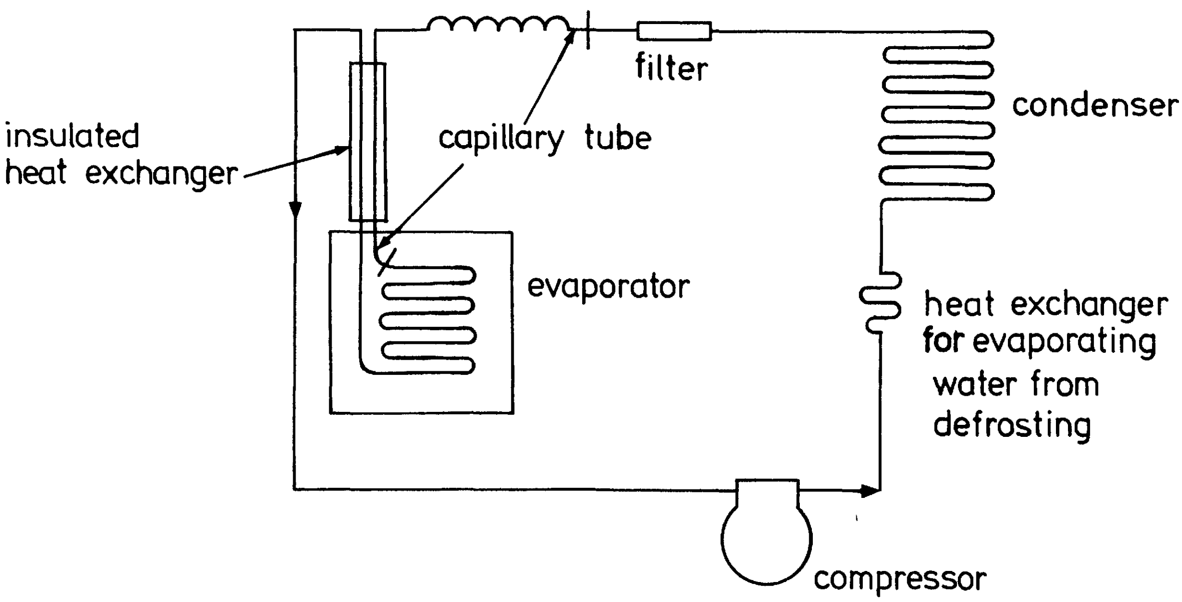


Figure 9. Diagram of the cooling system.

The refrigeration system is controlled by a Danfoss thermostat 090 B with its sensor attached to the evaporator. The compressor is started when the temperature of the sensor exceeds 3.5°C and stopped according to the setting of the thermostat in the range -10°C to -20°C.

Initially a COP of 1.5 or more was aimed at. At a later stage of the project an energy analysis was carried out by means of a computer programme(7). The result indicated that the design temperatures of the cooling system would be : condenser temperature 31°C , evaporator temperature -2.5°C, COP=2.0, and a daily electricity consumption of 0.29 kWh at ambient temperature 25°C and inside temperature 5°C.

As the evaporator temperature at first was expected to be around -2.5°C, a special thermostat stopping the compressor according to temperature in the range -4 to -15°C, was developed. When it later turned out that the evaporator temperature in fact was lower, the formerly mentioned thermostat was used.

The weak point of the cooling system is the function of the capillary tube. In general, the ability of a capillary tube to actually control the flow of refrigerant is not very good and often vapor appears at the end of the condensor. This is necessary in order for the tube to control the pressure decrease.

Another weak point is the function of the thermostat. The temperature of the evaporator is controlled, but it would be more appropriate to control the temperature inside the cabinet, as this temperature is influenced not only by the temperature of the evaporator, but also by the varying heat load on the refrigerator.

VARIOUS TESTS OF THE REFRIGERATORS

Of the seven cabinets that were insulated, three cabinets were stored away and four went on in the assembling process (see Fig. 10). Two of the prototype refrigerator cabinets were equipped with the modified low energy compressors from Danfoss mentioned earlier. Two cabinets were equipped with the smallest standard compressor from Danfoss (TL2A).

Due to a soldering defect of a capillary tube, one of the refrigerators with standard compressor failed to contain the refrigerant. It was used as a model in the photo-study and afterwards stored away. The cooling systems of the three remaining refrigerators were filled with freon refrigerant, R12.

In the following, the refrigerator equipped with the smallest standard compressor from Danfoss (TL2A) will be designated "LER1". The two other low energy refrigerators, equipped with the two modified compressors, will be designated "LER2" and "LER3". In all three prototypes the formerly mentioned enlarged and improved evaporators and condensers were used.

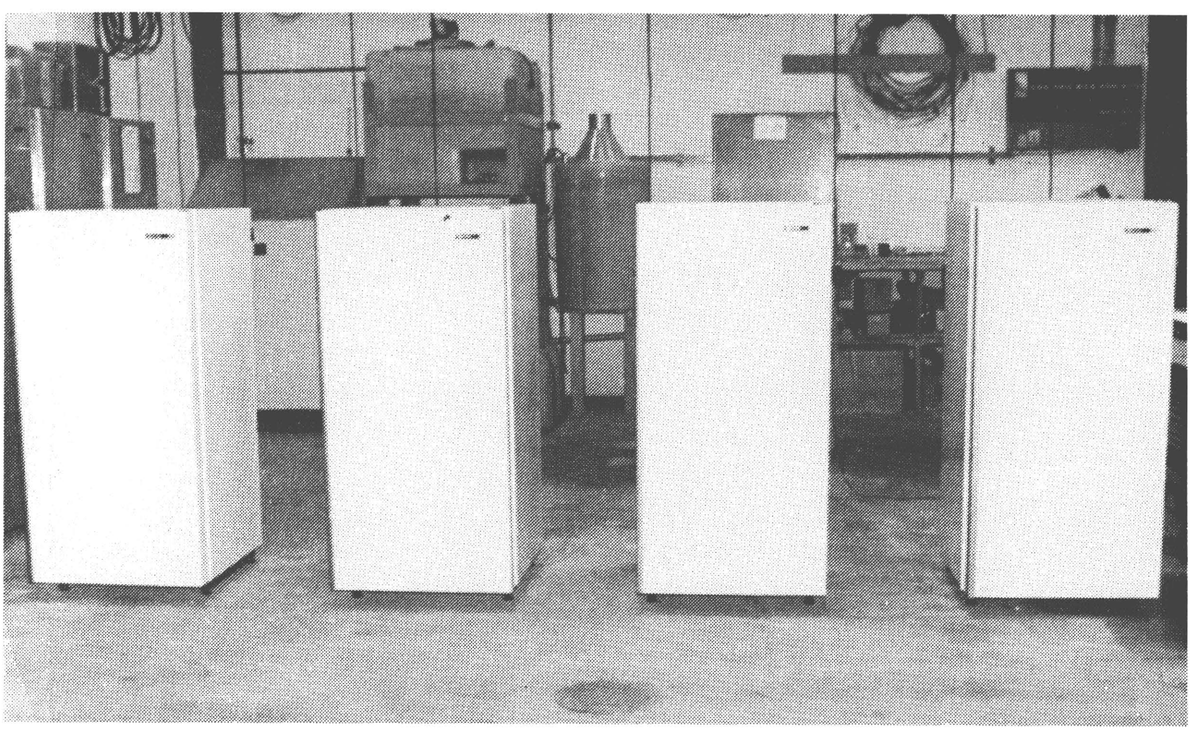


Figure 10. Four prototype refrigerators were equipped with cooling systems.

General consumer features of the refrigerators

The Danish Government Home Economics Council (Statens Husholdningsråd) operates test laboratories for households appliances. Here refrigerators on the Danish market are tested periodically with respect to various features, one of which is energy comsumption. They agreed to test one of our prototypes, LER2 (11).

The Home Economics Council found that the net inner volume (usable volume) was 200 liters in LER2 compared with 206 liters in the reference K215. This deviates somewhat from Gram's evaluation of net inner volume, due to minor differences in definition. Gram found a net inner volume of 186 litres for LER and 200 litres, for K215 (10). The part of the volume which is available in the door is according to the Council's tests increased from 44 liters in the reference K215 to 62 litres in LER2.

Refrigerator type	Net inner volume	Volume in door	Shelf area
LER	200 litre	62 litre	107,8 dm^2*
K215	206 litre	44 litre	108,8 dm^2

* when fully equipped with shelves

Table 1 Volumes and areas in the low energy refrigerator LER and the Gram refrigerator K215, used as a reference, according to Danish Government Home Economics Council.

By mistake the LER2 sent to the evaluation at the Home Economics Council was not equipped with all the shelves it has space for. (In all Gram refrigerators the shelves in the door are all shaped as removable containers). Therefore the total shelf area was found to be only 84,1 dm^2 in LER2 compared to 108,8 dm^2 in K215. If fully equipped with containers in the door and one more shelf in the cabinet, LER2 was found to have a total shelf area of 107,8 dm^2 , which is essentially the same as the area in K215.

Due to the way the LER prototypes were built, their outer depth is 3 cm above the standard. In actual production this can be avoided in the design, resulting in a 12 cm higher refrigerator or 15 liters less inner volume.

We can conclude that the 2oo litres of space in the low energy refrigerators, LER, is easier accessible than the 206 litres in K215 due to the fact that a larger portion of the space is located in the door and because of less depth of the shelves in the cabinet.

Various energy tests of the refrigerators

Energy consumption of the low energy refrigerators LER has been tested by four laboratories namely at Danfoss, Gram, Danish Government Home Economics Council and Physics Laboratory III.

If not specified otherwise, the following results refer to standard test conditions : ISO/R 824(19), DIN8950 (8). These prescribe an ambient room temperature of 25^{o}C, an internal temperature of 5^{o}, no door openings, and walls behind and on the sides of the refrigerators, according to detailed norms, see figure 11. The relatively high room remperature is used in the standard test partly to compensate for lack of door openings.

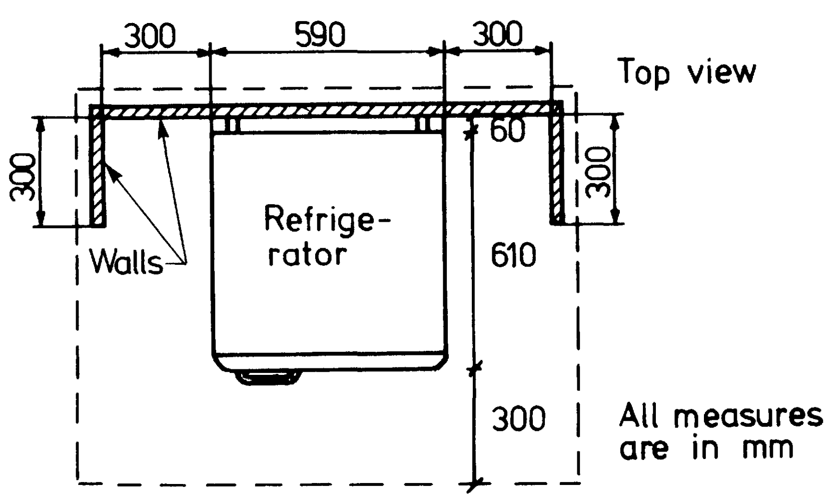


Figure 11. Top view of the set up prescribed for standard tests of refrigerators.

Tests at Danfoss

Danfoss has tested all three low energy refrigerator prototypes (9).

Energy consumptions measured by Danfoss are shown in Table 2.

Refrigerator type		Electricity consumption
LER1	(C)	0.36 kWh/24h = 131 kWh/year
LER2	(B)	0.30 - = 109 -
LER3	(A)	0.285 - = 104 -
LER3	(A1)	0.28 - = 102 -

Table 2. Test results from Danfoss. The A, B, and C refer to prototype identifications used by Danfoss. (A1) refers to test with reduced capacity of the compressor, obtained through reducing the speed of the motor (the revolution per minute, RPM) by lowering the frequency from the normal 5o Hz to 36 Hz. The LER1, (C) is equipped with a standard compressor.

As the original target was to reach a consumption of 0.31 kWh per day at standard test conditions, it seemed that our goal has been reached. However, we still lacked to find out whether the consumption in normal use would reach the target of 0.27 kWh per day (100 kWh per year).

Despite the low electricity consumption of the prototypes equipped with the modified compressors, their refrigeration system is working rather inefficiently. This is due to the fact that the compressor, as expected, has too large a capacity, although it is the smallest type available. The system is running only around 2o percent of the time, and during this short time the heat exchangers must transfer the heat from the cabinet to the surroundings. This requires relatively high temperature differences and the thermodynamic efficiency will be low. The evaporator temperature at the end of the cycles turned out to be -10°C. It was estimated that the capacity of the improved compressor was more than twice as large as necessary.

By reducing the motor speed to about 2025 RPM from the usual 2900 by lowering the frequency as mentioned, see test (A1), the consumption was hardly changed at all, but the running time was increased to 32%. It should be noted that the setting of the thermostat was unchanged in this test. This implies that the temperature of the evaporator was the same as usual at the end of each cycle. Hereby the advantage of the reduced capacity of the compressor, namely to increase the evaporator temperature during performance, was not utilized, and therefore no significant change in energy consumption could be expected. The lowering of the RPM was modest - only 30% - because the oil pumping system for lubrication restricts the range of operation.

Tests at Gram

Gram tested a K215 and one of the low energy prototypes, LER3 (10) as shown in Table 3:

Refrigerator type	Electricity consumption
K215	0.73 kWh/24 h = 266 kwh/year
LER3	0.37 - = 135 -

Table 3 Energy consumption according to standard tests at Gram.

The consumption of LER3 is higher than the previous measurements at Danfoss, Table 2. Cooling system and thermostat were, however, maladjusted, for instance resulting in an evaporator temperature of -19°C and standstill periods of 1 1/2 hours.

Beside the standad test, Gram also tested the two refrigerators under some simulated user condition. During this test the ambient room temperature was still 25°C and the door of the refrigerator was opened 51 times per 24 hours. Six standard one kilogram packages at 25°C were put into the cabinet per 24 h. Energy consumption with Gram's user test is shown in Table 3.

Refrigerator type	Electricity consumption
K215	0.94 kWh/24 h = 345 kWh/year
LER3	0.60 - = 220 -

Table 4 Energy consumption according to Gram's users tests.

Note that the user test at Gram was made with an ambient temperature of 25°C whereas the actual average ambient temperature must be expected to be somewhat less. The low energy refrigerator consumed 125 kWh less than the K215 per year in this user test even though cooling system and thermostat turned out to be maladjusted. We will return to the issue of normal use in a later section, page 35.

Tests at the Danish Government Home Economics Council

Danish Government Home Economics Council has tested the standard energy consumption of K215 and LER2 with the results in Table 5:

Refrigerator type	Electricity consumption
K215	0.74 kwh/24 h = 270 kWh/year
LER2	0.35 - = 128 -

Table 5 Results of tests at Danish Government Home Economics Council. See comments in text.

It should be mentioned that the Home Economics Council found it impossible to keep the temperature inside the cabinet as high as 5°C. The lower temperature inside the cabinet explains the relatively high consumption measured in this test of the LER2. The malfunction of the thermostat has later been corrected at Physics Lab III.

Test at Physics Laboratory III

During most of the project period we had no facilities for testing refrigerators at Physics Lab. III, such as a room with controlled ambient temperature. In the last phase of the project, however, we established a set up for standard test conditions, including a reasonably good control of ambient temperature. In this test set up we found the results for electricity consumption shown in Table 6. For the reference refrigerator K215 we found a somewhat higher electricity consumption than what Gram and Danish

Home Economics councils found, and higher than the 250 kWh per year we anticipated in Fig. 1. Given our rather primitive test room, some of the discrepancy might be ascribed to uncertainty in our measurements.

Refrigerator type	Electricity consumption
K215	W = 0.84 kWh/24h = 307 kWh/year
LER2	W = 0.28 kWh/24h = 102 kWh/year

Table 6 Results of standard tests at Physics Lab. III. These results are corrected for deviations of temperatures from standards, as explained later.

The electricity consumption of a refrigerator can be expressed as

$$W = Q/COP + W_a$$

where COP = Coefficient of Performance expresses how efficient the refrigeration system is, and Q is the heat load to be removed from the cabinet. W_a is the auxillary uses of electricity for lamps etc., which is essentially zero in our cases.

In order to be able to evaluate the various conservation measures and the electricity consumption under different conditions, such as in normal use, we want to determine not only W, but COP and Q explicitly. It turns out to be rather difficult to measure COP in a refrigeration system which is installed in a refrigerator. We have to find ways to determine the heat load, Q. Knowing Q and W, we can calculate COP.

Measurements of the overall heat transfer coefficient

Under standard test conditions with closed door the heat load consists only of heat transmitted to the cabinet from the surroundings through the walls etc. This heat load is described by

$$Q = kA \cdot (t_o - t_i)$$

where t_o and t_i are the temperatures outside and inside the cabinet, respectively, and kA is called the overall heat transfer coefficient. A is representing a medium area of the wall insulation and k is the average heat conductance per unit area of the combination of the wall insulation and the inner and outer heat transfer between air and walls. The average k also includes the heat transmitted through the gasket material and other cold bridges.

In order to evaluate the heat load, the first step was to measure the actual overall heat transfer coefficient of the cabinets, kA. In designing the cabinet of the prototype, a certain coefficient of thermal conductivity of the polyurethane foam was assumed, but we had no measurements of whether the actual insulation standard was higher or lower than what we had designed it to be. The following experiments to measure this are described in a note in Danish (13).

The overall heat transfer coefficient, kA, can be calculated from measuring corresponding values of Q, t_o, and t_i.

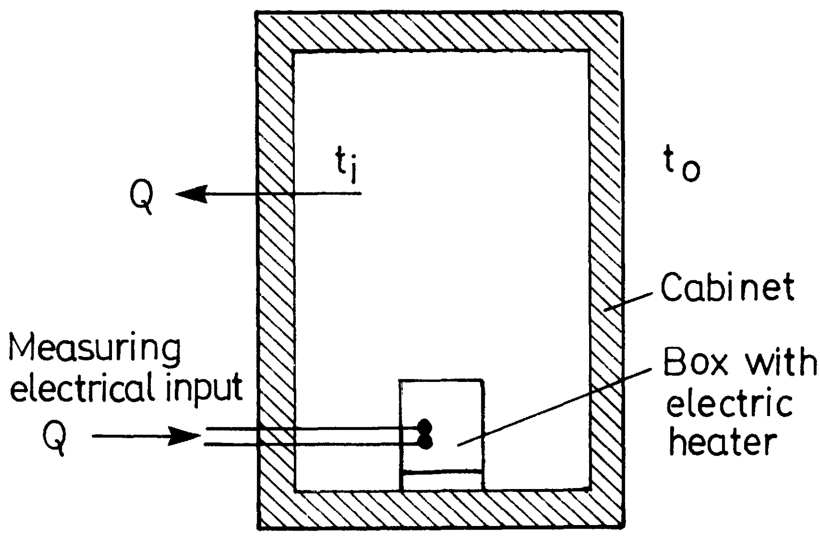
Under stationary conditions the heat removed from the cabinet is equal to the heat, Q, admitted into the cabinet. To simulate a refrigerator where $t_i < t_o$ and Q is positive we need a measurable heat sink. Obviously, we could not use the refrigeration system for that, so we turned it off. Instead we could use melting ice as a heat sink. However, it would be easier to control and measure heat <u>supply</u> into the cabinet from a heat source in the form of electric resistance heating. This would result in $t_i > t_o$ and a transmisson of heat <u>out</u> from the cabinet through walls. Both methods should be usable if we can assume that the thermal conductivity of the foam, etc., and hence kA, does not change with temperature, or rather that we can make a temperature correction. We made two experiments, one with a heat source ($t_i > t_o$) and one with a heat sink ($t_i < t_o$).

First we determine the overall coefficient, kA, with a heat source, that is, at temperatures t_i in the cabinet above the ambient, see figure 12. The cabinet was heated electrically, hereby creating a stationary temperature at which the heat given off by heat transmission equals the heat supplied. Great care was taken that no movements of the air inside the cabinet were created and that the temperature inside the cabinet at top and bottom were the same.

The experiment was carried out for both the LER2 and our reference refrigerator K215. The stationary temperatures and the corresponding heat supplied are shown in Table 7. As the thermal conductivity of the polyurethane foam decreases with decreasing temperature (12), a correction ammounting to app. 6 percent was made to adjust it to the normal refrigerator condition of 15°C average materials temperature.

Refrigerator	t_o	t_i	Q	$kA_{measured}$	$kA_{corrected}$
K215	24.7°C	35.3°C	16.3 Watt	1.538 W/°C	1.454 W/°C
LER2	23.8°C	40.7°C	15.05 -	0.886 W/°C	0.823 W/°C

Table 7. Measurements to determine the overall heat transfer coefficient kA by heating the interiour of the cabinet.

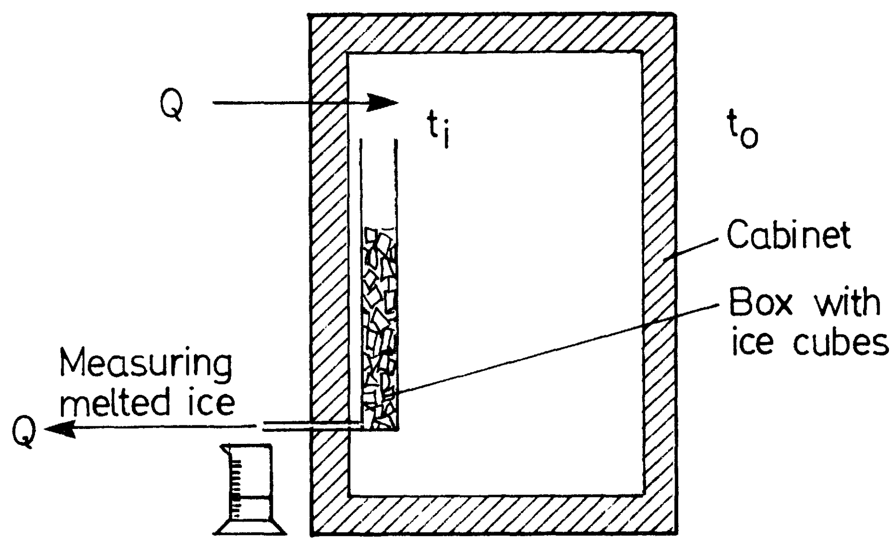


Figur 12. Diagram of the set up for measuring the overall heat transfer coefficient kA at cabinet temperature t_i higher than the ambient temperature t_o.

The results showed that the overall heat transfer coefficient of the LER2 was reduced by 43% in comparison to K215.

In absolute values the overall heat transfer coefficient was 0.82 W/°C for LER2 and 1.45 W/°C for K215. In comparison, the original target was to attain an overall heat transfer coefficient of 1.2 W/°C for LER2, equivalent to a heat transmission of 24 W at standard test conditions with 20°C temperature difference between the inside and the outside of the cabinet. Thus, the actually attained result was considerably better than what we set out to reach, but the starting point for the K215 was also better than anticipated. We can conclude that the measurements of heat transfer coefficient by heating the cabinet points towards a lower heat conductivity for the polyurethane foam than the 0.029 W/m·°C we anticipated in our calculation in designing.

The second experiment to determine the overall heat transfer coefficient, kA, was carried out with a heat sink (or a cold source) and only for LER2. The cabinet of the LER2 was cooled by means of a box made of aluminum which was filled with ice cubes. The water from the melting ice was led to the outside of the cabinet through a tube, see Fig. 13. The steady state temperatures and the flow of water was used to calculate kA.



Figur 13. Diagram of the set up for measuring the overall heat transfer coefficient kA at cabinet temperature t_i below the ambient temperature t_o.

The result of this ice box experiment indicated an 11% lower kA-value than the temperature corrected value found through the heating experiments. One explanation for this difference could be that stationary conditions, especially concerning the temperature of the ice cubes, were not obtained. However, another explanation could be that the thermal conductivities of the polyurethane foam and the other materials are more influenced by temperature than what is listed for polyurethane (12) and used in our correction of kA from the heating experiments.

For the calculation of the COP-values, we used the results found from the experiments with electrical heating.

Determination of COP

The heat load Q is determined from the overall heat transfer coefficient kA found from experiments, see Table 7, and from the desired temperatures inside and outside the cabinet through

$$Q = kA(t_o - t_i)$$

The average electric power W is measured for conditions close to the desired and then corrected for the deviation since we have not been able to establish the desired temperatures with sufficient accuracy.

Finally COP for the desired conditions is calculated from Q and the corrected value of W through

$$COP = \frac{Q}{W}$$

Correction for deviations from desired conditions

In the tests at Physics Lab. III we have as mentioned not been able to maintain the desired temperatures outside and inside the refrigerator. Deviations have typically been 1 to 2°C. The electricity consumption measured has been corrected for these temperature deviations by the following approximate correction considerations. The deviations in temperature affect the average electric power through 1) heat load and 2) COP of cooling system.

Heat load, Q, during tests is proportional to the temperature difference $t_o - t_i$. Since this difference is around 20°C the heat load measured at the actual temperature difference $(t_o - t_i)_{actual}$ should be corrected by subtracting 5 percent/°C that $(t_o - t_i)_{actual}$ is higher than the desired. The correction is thus -5 percent/°C.

According to Figs. 7 and 8 COP decreases with increasing condensor temperature by approximately 2% per°C for both types of compressors. A change in ambient temperature t_o will to a good approximation result in a similar absolute change in condensor temperature. With this assumption we find that the correction of COP should be +2% per°C deviation in t_o from the desired.

A change in thermostat setting will cause a change in evaporator temperature and inside temperature t_i that are approximately equal. If we neglect a smaller change that will occur in condensor temperature we can read the COP's dependence on inside temperature from Figs. 7 and 8. The result is that the correction of COP should be -3% per deviation in t_i from the desired.

A change in heat load from door openings or from warm goods will change the length of the off period but to a first approximation the condensor and the evaporator temperature will stay constant. COP will thus stay constant as well. This theoretical statement has been confirmed in an experiment where an extra heat load was introduced by means of a heating element.

COP at standard conditions

By using the derivatives of COP with respect to inside and ambient temperatures

$$\frac{1}{COP}\frac{dCOP}{dt_i} = 3.0\%/^{o}C \quad \text{and} \quad \frac{1}{COP}\frac{dCOP}{dt_o} = -2.0\%/^{o}C$$

as estimated in the preceding section we find the values of COP at standard conditions as shown in the last column in Table 8.

Refrigerator	t_o °C	t_i °C	COP measured	COP standard
LER2	24.3	4.9	1.41	1.35 ≈ 1.4
K215	24.2	5.4	0.84	0.83 ≈ 0.8

Table 8. COP values for LER2 and K215 refrigerators. COPs at standard conditions are calculated from values measured at almost standard conditions.

In the original design it was anticipated that a COP somewhere between 1.5 and 2.0 at standard test conditions could be obtained for LER2, but as it turned out the actual COP was only 1.4.

The explanation for the COP being lower than anticipated is difficult to find. If a condensor temperature of 36°C and an evaporator temperature of -10°C is assumed (this should be a pessimistic assumption according to the measurements), a COP of 1.9 can be expected according to the compressor measurements made by Danfoss. The explanations for the COP being inferior to the anticipated value should probably be found in one or more of the following reasons :

- we might have measured an overall heat transfer coefficient that is not quite representative of the actual use of the refrigerator. For instance , the cold evaporator create a movement of the air inside the refrigerator different from that of the heater used in the experiment.
- the assumption of having pure liquid refrigerant without any vapor after the passage of the condenser is questionable
- the compressor is cold and hereby the viscosity of the oil is increased
- there is a loss in the motor at starting the compressor
- the fact that pressure is being equalized during the standstill of the compressor represents a loss of efficiency
- the efficiency of the compressor is measured at stationary conditions. Non-stationary conditions, like for instance the condensation of gas inside the evaporator during standstill, represent a loss
- a relay used for controlling the electrical circuit consumes 0.5 W when the compressor is running.

But there are also factors pointing in opposite direction, which make the picture more complicated. A cold compressor should for instance be more efficient than a hot compressor due to the vapors not being heated as much on entering the compressor-unit.

A Carnot cycle, based on the standard outside and inside temperatures, t_o and t_i, would have a

$$COP = \frac{t_i + 273}{t_o - t_i}$$

$$= \frac{5 + 273}{20}$$

$$= \underline{13.9}$$

The Carnot efficiency, defined as the actual COP divided by the theoretical Carnot-COP is found to be only around 10% in our LER2. This indicates that in theory there is plenty of room for improving the refrigeration system. Another basis for this improvement potential is the fact that the compressor is running only around 20% of the time. This also means that the heat exchangers are only being utilized roughly 20% of the time, and therefore the temperature differences are greater than they need to be.

ELECTRICITY CONSUMPTION IN NORMAL USE

We have found no European standards for what should be considered normal utilization of a refrigerator. When in use the total heat load derives from:

1) Heat transmitted through walls and doors.
2) Air exchange when the door is opened
3) Goods put in with higher temperature than the inside cabinet temperature.
4) Air infiltration through leakages along door gaskets.

The standard test conditions in Europe (8) prescribe no heat load from 2) and 3). Only heat transmitted, 1), is assumed, because 4) is essentially zero for the new refrigerators tested. In an attempt to have 1) to represent the whole heat load, the ambient temperatue for standard tests is prescribed to be 25°C, which is higher than what is expected as average kitchen temperature.

In the following we will estimate what the heat load in normal use can be.

Heat transmission

This heat load depends on the temperatures of the room, t_o, and of the cabinet t_i. We will assume t_i = 5°C.

Room temperature has been suggested to be on the average 21°C in a German investigation (16). A Dutch investigation (17) found an average room temperature during the fall of 18°C. However, over the whole year the average room temperature was estimated to be 21°C. The refrigerator manufacturer Gram, maintains 25°C as ambient temperature in what they describe as users test. These large variations in assumptions on temperature conditions in normal use illustrate the problems in setting a standard.

In the Danish climate we have found it reasonable to assume an average kitchen temperature of 21°C like in the German investigation. This average corresponds to 20°C in the heating season and up to 24°C during midsummer.

From the overall heat transfer coefficients found earlier, Table 7, we now find the heat load Q_t from transmission for LER2 and the reference to be on the average

LER2: Q_t = 13.2 Watts

K215: Q_t = 23.3 Watts.

Opening of door

A Dutch investigation (14) found that on the average 24 door openings can be expected per day. This investigation also estimates the heat load derived from these door openings. It is found appropriate to count on all the air in the cabinet being exchanged once each time the door is opened. The heat load from this air exchange derives from the difference in enthalphy between the outgoing air and the ingoing, due to different temperatures and absolute humidity. In other words the warm air let into the cabinet has to be cooled from t_o to t_i and some of the water vapor condensates on the evaporator. If the air is cooled from 21°C to 5°C and the relative humidity is assumed 60% both inside and outside, the heat load from 24 door openings per day is approximately

$$Q_d = 2.2 \text{ Watts}$$

for both LER2 and K215.

These assumptions and results fit well with what we found in an earlier analysis (1,2), based on 20 door openings. The heat load was found to be 2.1 Watts in this analysis.

In the German investigation (15), it is found that the temperature of the evaporator affects the heat load from door opening. A lower evaporator temperature causes a higher heat load. This effect (which would favor LER2 over K215) has, however, not been included in our resutls, mainly because we have doubts whether the method used gives the correct result.

Cooling of food

Some of the food (and containers) placed in the refrigerator will have a temperature higher than the kitchen temperature such as left-overs not cooled down before stored away. Some of the food will, however, be colder than the kitchen temperature, such as food just brought home from the stores' refrigerators or just brought in from outside. On the average, we will assume the temperature of food, etc. being placed in the refrigerator to be the same as that of the kitchen, that is in our case 21°C.

The amount of food, etc., placed in the refrigerator is estimated to be 4 kg per day. We assume an average specific heat capacity of the food to be equal to that of water, that is 4.2 kJ/kg·°C. If we ignore the condensation of moisture derived from the food we find a heat load for both LER2 and K215 of:

$$Q_f = 3.1 \text{ Watts.}$$

Air infiltration

When a refrigerator has been used over some years leakages might develop along the door gaskets, which then should be replaced. Often this is not done in time, and the continous air infiltration can be a significant contribution to the heat load. In our earlier analysis (1,2) we have estimated this heat load, Q_a, from air infiltration to be 3.8 Watts on the average over the lifetime of the refrigerator. We will here, however, ignore this contribution assuming we are dealing with new or well maintained refrigerators.

Electricity consumption in normal use

For "normal use" conditions the transmission heat load Q_t and COP are calculated in the same way as for standard conditions i.e. from measurements close to "normal use" conditions which are corrected to "normal use" conditions.

Table 9 shows the steps in calculating the electricity consumption, W, in "normal use" compared to that in standard test conditions. The annual savings by using the low energy refrigerator LER2 instead of the reference K215 is seen to be 163 kWh/yr in normal use and 204 kWh/yr when based on standard tests.

It should, however, be kept in mind, that the conditions chosen for the "normal use", such as 21°C ambient temperature, is very uncertain.

	LER2 normal use	LER2 standard	K215 normal use	K215 standard
Q_t	13.2 Watts	16.5 Watts	23.3 Watts	29.1 Watts
Q_d	2.2 -	0.0 -	2.2 -	0.0 -
Q_f	3.1 -	0.0 -	3.1 -	0.0 -
Q_a	0.0 -	0.0 -	0.0 -	0.0 -
Q	18.5 Watts	16.5 Watts	28.6 Watts	29.1 Watts
COP	1.56	1.41	0.94	0.83
W	11.9 Watts	11.7 Watts	30.4 Watts	35.0 Watts
W	0.28 kWh/24h	0.28 kWh/24h	0.73 kWh/24h	0.84 kWh/24h
W	104 kWh/yr	103 kWh/yr	267 kWh/yr	307 kWh/yr

Table 9. Heat loads, Q, Coefficients of Performance, COP, and electricity consumption, W, calculated for the low energy refrigerator LER2 and the reference K215 at standard conditions and in a"normal use" based on a kitchen temperature of 21°C.

With the conditions for normal use chosen here there appears for LER2 to be essentially no difference between electricity consumption in normal use and under standard test conditions, see Table 9. For K215, the consumption in normal use is 11% less than that under standard test conditions.

The result for K215 is in reasonable agreement with a German investigation (16) in which it was found that the consumption of electricity for a refrigerator in a large household of 6 persons exceeded the consumption at standard-test conditions by only 3%.

A Dutch investigation (17) finds that the consumption in normal use is 40% less than the consumption at standard-test conditions, but in this investigation, the setting of the thermostat was not recorded and the average room temperature was found to be as low as 18°C.

The low consumption of K215 derives from the relatively small importance of the door openings and of the goods being cooled. The average COP turned out to be 0.94 which was slightly better than was measured at Physics Lab. III at standard-test conditions .

The electricity consumption of LER2 in normal use is 2.5 times less than the consumption of K215, equivalent of a saving of 160 kWh/year.

FURTHER IMPROVEMENT OF COOLING SYSTEM

Through the work reported so far we have achieved substantial savings in electricity consumption, and essentially reached our target of 100 kWh per year. Nevertheless the performance of the refrigeration system in the LER prototypes can in theory be improved further. Two major options are: 1) reduction of compressor capacity to fit the low load, and 2) improving the regulation ability of the thermostat.

In the following we will consider some of the possibilities for reducing the compressor capacity in theory and evaluate their feasibilities in practice.

Need for lower capacity

The main problem in the refrigeration system of LER is that the capacity of the compressor, the TL2A from Danfoss, seems to be much too large, even though it is the smallest available on the market. At standard test conditions, the running period of the compressor is only around 20% of the time, and at more normal room temperature of 21^{o}C and no user load, the running period is as low as 12%. Since the heat content of the two heat exchangers are small, compared tc the heat they transfer per period, they too will be utilized only 12-20% of the time. This implies that the temperature differences between the heat exchangers and their surroundings will have to be high, which result in a relatively low COP of the refrigerator system. Alternatively, it implies, that the heat exchangers have to be large to maintain a reasonable COP, hereby increasing the cost of the refrigerator. The problem derives from the fact that the compressor manufacturers mainly have directed their efforts towards improving the performance of the compressors at conditions prevailing in freezers where the evaporator temperature is much lower and the necessary capacity of the compresser higher (25).

We therefore set out to find a realistic way to reduce the cooling capacity of the compressor. The following four options were considered:

1) Reducing the speed of the motor.
2) Reducing the compressor stroke.

3) Using a refrigerant with less cooling capacity per unit of vapor volume.
4) Alternatives to reciprocating compressors.

If we aim at a running time of 50% after decreasing the capacity of the compressor, the capacity seemingly should be lowered by a factor of 2.5 at standard tests. However, when a smaller compressor is used the COP of the whole system improves, and hence it would be appropriate to strive for larger reduction factor than 2.5, rather 3.5.

Operating condition of LER

Before we turn to discuss the above listed options for reducing the capacity of the compressor, we will define more closely the outset operating conditions.

Figure 14 shows the temperature developments during normal operation t 21°C with no user load. Temperature of the evaporator varies between +3.5°C and -11°C, with a mean value during running periods of app. -4°C. The condenser temperature varies between 36°C and 21°C with a mean value during running periods of app. 33°C. The graph shows that the thermostat cuts off the compressor when the temperature of the evaporator reaches -11°C. Other experiments (see Figure 16 later) have shown that this is close to the steady temperature of the evaporator when the cooling system is in equilibrium at a cabinet temperature of +5°C.

Reduced motor speed

In our search for ways to reduce the compressor capacity, we will first consider the option of simply running the compressor at lower speed, since this will also reduce the energy loss due to friction.

When the compressor is running, the power loss from friction is roughly proportional to the square of the velocity of the moving parts. If we assume that the slower running compressor would have to run correspondingly longer than the ordinary one in order to provide the same cooling, the total energy loss due to

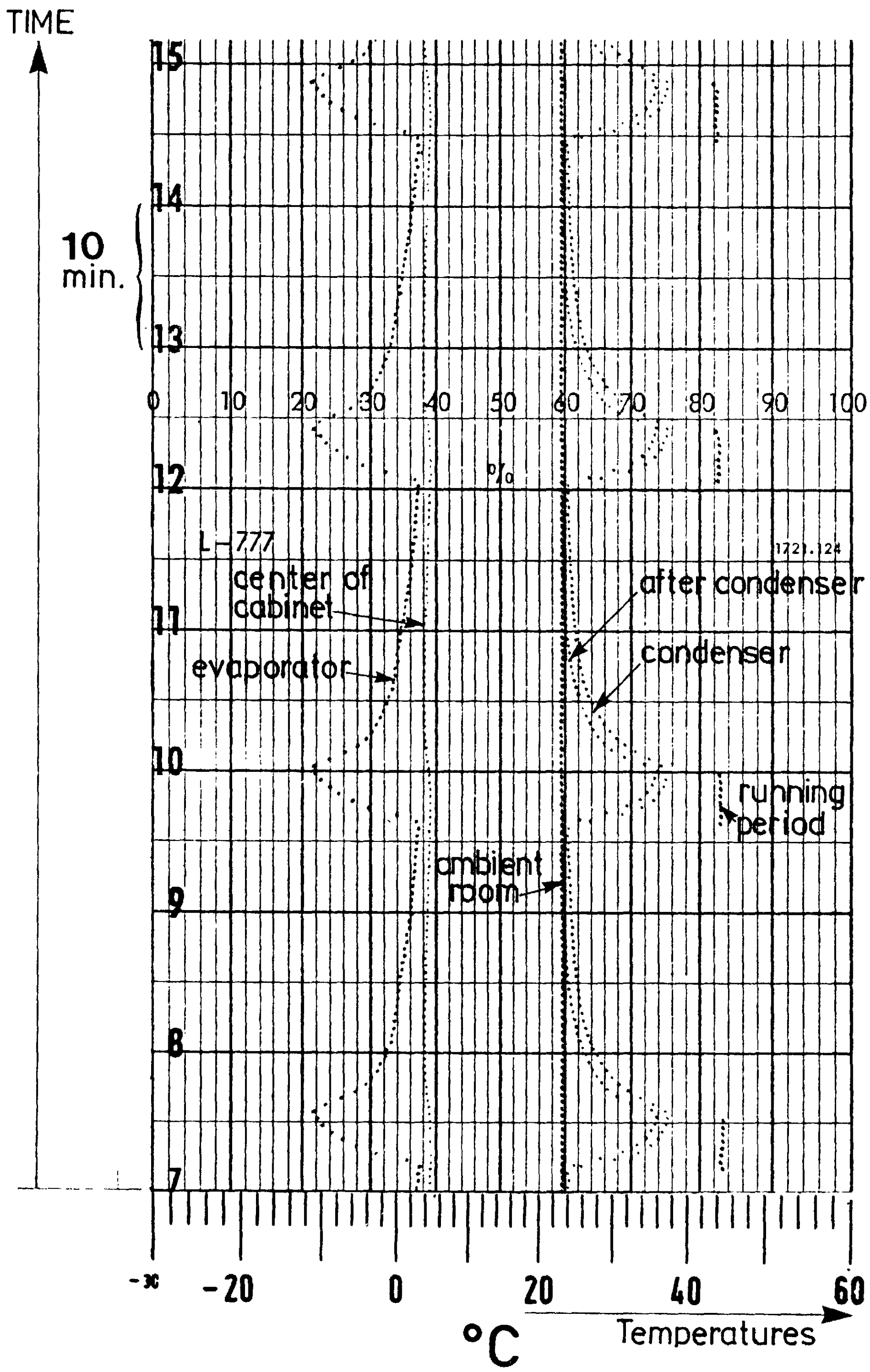


Figure 14. Temperature variations at different positions in the LER during normal operation with no user load. The condenser temperature is measured at a position at one third of the way through the condenser.

friction would be proportional to the velocity, not the square of the velocity. However, if we manage to achieve our goal, namely to inrease the efficiency of the whole system, the running period will not be increased inverse proportional to the velocity. It can be rather complicated to evaluate the reduction in energy loss from friction, but it seems safe to suggest that it should be proportional to the reduction in compressor speed.

Reduction in the rotational speed of the compressor, does, however, create a practical problem. The lubrication oil of the compressor is circulated by a centrifugal pump system, built into the compresor. The capacity of this pump system declines with reduced rotational speed. Danfoss (34) has suggested that only a moderate reduction from the normal 2800 rpm to 1700 rpm can be tolerated, if sufficient lubrication is to be ensured. This corresponds to a reduction in compressor capacity by a factor of 1.7. Speed reduction beyond that will require modifications of the lubrication system.

The speed of the motor can be reduced in two ways:

1) Increasing the number of poles on the motor,
2) Reduce the frequency of the AC power by means of a frequency converter.

If the number of poles is increased from the present 2 to 4, the rational speed will be lowered from approximately 2800 rpm to around 1300 rpm. This would require the above mentioned modifications of the lubrication system, and has not been tested experimentally in this project. We will, however, evaluate the effect on the overall efficiency of such a change.

If the speed of the motor is reduced the evaporator temperature will increase and the condenser temperature will decrease. The pressure difference across the compressor will thus decrease and so will the torque of the motor.

If an ordinary two pole motor is rewound for four pole operation, the maximum available torque will be essentially unchanged.

The loss caused by friction in the compressor is, as described above, reduced considerably because of the lower speed, whereas the electrical loss caused by resistance in conductors is reduced to the extent that the necessary torque is reduced. Finally the hysteresis and the eddy current loss in the magnetic material can be reduced if the magnetization is reduced to the level necessary for the required torque.

The loss from leakages around the piston is likely to increase relatively when the velocity is reduced. Despite of the uncertainty about this it seems safe to conclude that by using a 4-pole motor with the same size as the ordinarily used 2-pole motors, the overall efficiency of the compressor motor unit can be maintained or even increased.

We have found some references to the use of pole changing for hermetic compressors (27,28,29,30). In some cases, 4-pole motors have actually been used in order to lower the friction losses. But the compressors with pole changing were in general larger than what we are looking for. We would like to have a usual 2-pole compressor equipped with the option of 4-pole windings to lower the capacity, and with an appropriate lubrication system. Such a compressor would be suitable, not just for low energy refrigerators, but also for freezers, where the load varies significantly and where a two speed compressor probably could save electricity.

So far, no European compressor manufacturers have found it worth while to produce a low capacity 4-pole compressor, and we have - as mentioned - not found it possible to include such compressor changes in this project.

Reducing the compressor speed by means of a <u>power frequency converter</u> seems to be a more obvious solution, particularly for experimental purposes. Still, however, we face the problem of lubrication, which limits our speed reduction to only 1700 rmp from 2800 rpm.

A single experiment with running LER at 1700 rpm has been carried out by Danfoss, as shown in Table 2. No significant savings seem to be achieved, probably because the whole refrigeration system with thermostats, capillary tube, etc. had not been adjusted to the new compressor capacity.

In the future, small 4-pole compressors or 2-pole compressors with power frequency converters will probably be marketed at a reasonable price, since there seem to be an increasing market for them, even for use in some of the refrigerators models on the market today.

Reducing compressor stroke

Instead of lowering the speed of the compressor, its capacity can be reduced by reducing the stroke volume (piston displacement). We will mainly look at the possibilities - and the effects - of reducing the stroke of the piston, rather than its diameter.

One of the problems of reducing the stroke is that the dead space (clearance volume) will increase in relative terms, if no measures are taken to reduce its absolute size. In other words the volumetric capacity for constant stroke volume - the volumetric efficiency - will be lowered. A lower capacity is not directly a problem in our case, since that is actually what we want, but since some of the losses, such as the friction loss, are not reduced proportionally, the overall efficiency will suffer, if the dead space is not reduced.

One way to reduce the dead space is to use a MCCT-piston (32), which employes a small jut on top of the piston, filling out most of the volume of the discharge part, when the piston is in top position. For the present geometry of the small Danfoss compressor, however, the jut might harm the inflow of suction gas.

Another way to decrease the impact of the dead space is to use smaller diameter and longer strokes of the piston. This, however, will increase the relative friction loss, and is not considered as an option here.

Two ways are available for reducing the stroke:

1) Short circuit part of the stroke
2) Build a compressor with shorter stroke.

The first option of short circuiting implies drilling a hole in the cylinder wall about halfway through the stroke. Thereby we establish a short circuit between the compression and the suction side during the initial stage of the compression. The result is that only approximately half of the stroke is active.

For experimental purpose making a short circuit seems to be the easiest way to reduce the active stroke. A Danfoss TL1A compressor with circuit was supplied by Danfoss, who also measured its performance. Like in the normal compressor, the "Direct Intake System" was employed, and furthermore, the motor windings were adjusted to the reduced load. Time did not allow us to actually test this compressor installed in a refrigerator within this project.

Actually the volumetric capacity is not halved, since the first half of the stroke is partly active due to the smallness of the hole, which does not allow the pressures to equalize sufficiently fast.

Calculations based on the Danfoss measurements also indicate that the actual cooling capacity of the compressor by the short circuit is reduced, not by a factor of 2, but rather around 1.5.

Since friction in the cylinder and bearings of the compressor with short circuit remains roughly the same as without the circuit, this way of reducing compressor capacity can not be considered a final solution to the problem.

Building a compressor with reduced stroke volume is not possible within this project. However, that would be a way to reduce capacity <u>and</u> friction losses, since the movements of the piston are smaller. Such a change in production would require large investments, and appearently, no manufacturers have taken that step. However, as mentioned earlier, the market for low capacity, efficient compressor is increasing and reduced stroke volume is likely to be one of the options considered by manufacturers today and in the near future.

Changing refrigerant

Usually refrigerant R12 is used, as it has got a high cooling capacity per unit of vapor volume. If refrigerant R114 is employed, the capacity of the compressor is automatically lowered, since the cooling capacity per unit of vapor volume is less than when R12 is used.

Calculations indicate that the evaporator temperature at equilibrium will be around -7^{O}C instead of -12^{O}C (see Figure 16). Condensertemperature will be around 35^{O}C instead of 36^{O}C. This points towards an increase in COP of app. 15%. However, the coolling capacity is reduced to app. half, so the running time will be roughly doubled. So will the frictional loss and thereby amont to app. 40% of the electricity consumption when R114 is used instead of app. 25% with R12.

Various adjustments in motor and capillary tube will have to be made if we were to change refrigerant, and since the outlook, as indicated above, is not very good for an overall improvement, we have not conducted experiments within this project.

Alternative compressor principles

So far we have discussed the potentials for making small scale, efficient reciprocating compressors. Since the price for this type of small compressors is nearly independent of the capacity, not much is saved in price by making them very small, and it might be appropriate to investigate whether other principles are better suited.

Bellow compressor is one alternative (35). A bellow is a closed chamber, whose colume can be readily increased or decreased causing suction and compression. The bellow is made of a synthetic material which can stand the deformation, and the change in volume is generated by the vibrations of an electromagnet. This concept seems promissing. The main difficulty is whether any bellow material can stand up to the chemical attact of refrigerants for extended periods in the rough temperature conditions.

Vibrator compressor is based on a somewhat similar principle (38). Also in this case vibrations are generated by the push and pull of an electromagnet, but instead of a bellow, the usual concept of a metal cylinder and piston is maintained, see figure 15. One of the advantages of this compressor is that friction can be kept low, since the movement of the piston is produced directly by the electromagnet with no transmission loss and with transversal forces between piston and cylinder. Furthermore vibrator compressors are especially suited for small cooling capacities because of the simple construction. The disadvantage of this concept (as well as for the bellow concept) is that the amplitude of the vibration is difficult to control as it depends on the voltage supplied and the load on the cooling system. Therefore the outlet valve has to be constructed in a special way so that it is allowed to be pushed away from its usual resting position, thus creating more noise than a usual reciprocating compressor.

We have been able to identify just one manufacturer of vibrator compresors, namely Sawafuji Electric Co. in Japan. A French company named Combicool sell these compressors, and according to their brochure the cooling capacity is 46.4 W at

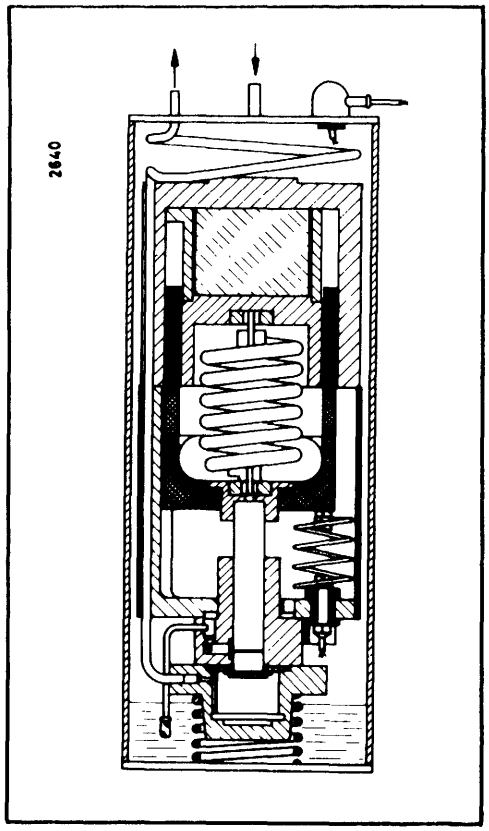


Figure 15. Diagram of a vibrator compressor. From ref. (40).

evaporator temperature -15^{o}C and condenser temperature 45^{o}C. At this condition the power consumption is 40W equivalent to a COP of 1.16, but the voltage should be 20 V and therefore a transformer is needed which induces an additional cost and a minor loss of energy.

At the same conditions as mentioned above the capacity of the smallest (improved) Danfoss compressor, the TL2A, is app. 80 W and the COP app. 1.5, and thus the cooling capacity is reduced by a factor 1.7, but at the cost of COP. Nevertheless, compared to the other options of reducing the capacity, the vibrator compressor might be an attractive possibility in the future, even though we lack information on its performance at high evaporator temperatures.

There have been several attempts by European manufacturers to make a mass production of the vibrator compressor. So far, however, with no success, one reason being the noise problem. In the future it seems that the vibrator compressor can be improved by electronic control, but presently we must rule it out as a low capacity compressor option for our low energy refrigerators because of noise problems.

Rotary compressors are allready used for refrigerator, for instance in Japan. Those on the market today have, however, a much too large capacity for our purpose in the LER. For instance, the smallest rotary compressor from Mitsubishi, the KL2 311 has a capacity of 105 W at an evaporator temperature of -23°C and a condenser temperature 54°C. At the same conditions, the improved version of the TL2A reciprocating Danfoss compressor we use has a capacity of 42 W and is vastly oversized. For our use we had to abandon the use of rotary compressors, but it could be a future option if low capacity rotary compressors with reasonable efficiencies can be developed.

Improvements of the thermostat

We have experienced some problems with the thermostat, which is of the mechanical type. The thermostat did not turn off at the right moment of the duty cycle. There are at least three possible reasons for that:

1) The sensitivity is too low (the hysteresis too high) to ensure accurate operation.
2) The thermal contact between the sensor tube and the evaporator is too poor to enable the sensor tube to follow the rapid temperature drop of the evaporator under the duty cycle.

All three problems can be essentially eliminated by using an electronic thermostat with sufficient gain fitted with a small electronic sensor e.g. a thermistor whose thermal delay relative to the evaporator can be neglected. A detailed investigation of an electronic thermostat has not been performed in this project, partly because the electronic thermostats on the market today have a considerable energy consumption of their own which counteracts their potentially savings in the compressor system.

Conclusion on further improvements

None of the above mentioned ways of reducing the capacity seem ideal at present. Either the option involve more noise, too high extra costs, or too low efficiency. However, the demand for such low capacity refrigeration compressors is increasing, and more effort should be directed towards solving these problems.

With respect to the control system it seems likely that the inroduction of electronic thermostats can achieve large improvements, when they will be developed to be more energy efficient themselves.

EVALUATING THE ECONOMY

The economy of the energy savings of the 200 litres low energy refrigerator, LER, has been evaluated mainly by comparing it to that of the almost similar size standard refrigerator K215, used as a reference throughout the project. The basis for calculating the annual savings is an electricity price, which is typical for Denmark by 1984:

Electricity price: 0.80 Dkr/kWh.

We will use the pattern of utilzation described earlier as "normal use", see Table 9. The pattern of use, however, has for refrigerators much less impact on the economy than in the case of washing machines and cookers.

Annual savings with LER

From Table 9 we see that in normal use the annual electricity savings for LER is 160 kWh when compared to one of the best, presently on the market, K215. This corresponds to a saving of 130 Dkr/year.

If instead we compare to the average refrigerator in use by 1984, the saving is around 310 kWh or 250 Dkr/year, but we will in the following mainly compare to K215.

Extra investment in LER

The extra production cost of LER includes a larger outer casing (corresponding to that of a 285 liter refrigerator), 120 liter extra insulation foam, larger evaporator, modification of a smaller compressor unit, and some other minor changes. Total extra production cost is estimated to be 170 Dkr. in 1984.

The retail price in Denmark is around 1.9 times the production cost for refrigerators, but 32% of the retail price for household appliances consists of government taxes. It is most likely that the marginal price/production cost ratio will be smaller than the average 1.9. It is also likely that government taxes in the future will be differentiated according to energy consumption with lower taxes on efficient models. It seems, therefore, that we will be on the safe side by assuming the retail price increase for our efficient model to be 1.9 times the extra production cost, that is 320 Dkr.

It could be argued that the cost of the extra space, which the efficient refrigerator takes up in the house, should be included in the cost analysis. The extra space is 110 liter or 0.11 m^3, corresponding to 0.11/2.4 = 0.05 m^2 floor space. The marginal price for floor space is estimated to 1000 Dkr per m^2, and the cost of the 0.05 m^2 amounts to 50 Dkr. Total extra cost for the consumers to choose the efficient LER model will then be around 370 Dkr.

Economic payback

From the above we find:

Annual savings for consumer:	130 Dkr/year
Extra investment for consumer:	370 Dkr
Simple payback period:	2.9 years

If we assume an average lifetime of refrigerators of 15 years (19) we get:

Accumulated value of savings with no interest:	1950 Dkr
Annual rate of return	28% per year

In the extra investment for the consumer is included special household appliance taxes and VAT, all together 32% of the extra retail price. On the other hand, in the cost of electricity is also included taxes amounting to 38% of the consumer price. Excluding all taxes in our calculations will therefore only make small changes in the above economy calculations.

If, however, the 20% special Danish tax on household appliances was differented according to energy consumption, as a means to encourage the purchase of low energy models, this could easily eliminate the whole extra retail cost of low energy refrigerators.

We can conclude that even without any change in taxes, etc. the economy is very much in favour of the efficient LER refrigerator with rate of return of 28% (taxfree) or less than 3 years simple payback period.

ENVIRONMENTAL IMPACT

The environmental costs and benefits of introducing refrigerators like the LER prototypes instead of our reference K215 will be analysed. We will consider the change in environmental impact, not only of running the LER compared to K215, but also in producing it.

Extra energy embodied in LER

Rather than analysing the absolute energy input when a refrigerator is manufactured, we will confine ourselves to evaluating the extra energy consumption associated with manufacturing LER instead of the reference K215.

Extra energy input is of special interest to analyse since our target is to save energy. It is mainly associated with the additional material used in LER the most important of which are listed in Table 10.

Extra materials in LER

Material	Mass (kg)	Specific energy (kWh/kg)	Energy content kWh
Polyurethane foam	5.3	3	16
Plastic, inner cabinet	0.1	3	0
Steel, outer cabinet	4.6	12	55
Steel, condenser	0	12	0
Aluminium, evaporator	0.4	65	26
Total extra input			97

Table 10. List of the additional material used in LER as compared to K215. The condenser used in LER is of a different type than that of K215, and was actually 0.6 kg lighter. Energy input is counted as thermal energy, not electricity. Specific energy values are from ref. (20).

We assume that the extra energy in assembling and handling LER is much smaller than the 97 kWh embodied in the extra material. Totally we estimate that the total extra energy embodied in LER is 150 kWh thermal energy.

It should be pointed out that energy input in the various materials can be reduced by increasing energy efficiency in manufacturing them. One way is increased use of recycled material which only requires a small fraction of what it takes to produce materials from ore etc.

Energy payback period, EPBP, is defined as the ratio between extra energy embodied in the product and the annual energy savings achieved. We save around 160 kWh electricity per year compared to the reference. How much fuel should be ascribed to this amount of electricity, depend on whether the electricity is produced from combined heat and powerplants, from hydropower, or from plants producing electricity from fuel. In Denmark most power plants are combined heat and power plants, and around 0.5 unit of heat is produced per unit of electricity. This implies that instead of the usual multiplication with a factor of 3 to get the fuel consumpton we can use a factor of 2.5. The 160 kWh electricity saved therefore in Denmark correspond to 400 kWh thermal energy saved per year. The extra input of thermal energy in the LER was found to be 150 kWh, which is then paid back in saved energy in

$$EPBP = \frac{150}{400} \text{ years} = 140 \text{ days.}$$

In countries with electricity delivered from pure electricity plants, the payback period will be around 115 days. With electricity from hydropower the payback perod will depend on how we assume the extra thermal energy input to be produced, but even if we assume this to be in the wasteful way of electricity, payback period can never exceed 1 year. For EEC as a whole we estimate an average payback period of EPBP = 130 days.

Given an average lifetime of a refrigerator around 13 years we can conclude that despite the uncertainties in the above calculations there is no reason to worry about whether it pays in energy to introduce the suggested improvements.

Environmental costs of producing LER

The extra energy used to manufacture a LER refrigerator as compared to a K215 results in an extra air pollution, etc. If we - as an approximation - assumes that all the energy listed in Table 10 for manufacturing the extra steel, etc. is derived from coal, we find the extra emission of sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon mono-oxide (CO) and dust particles as listed in Table 11, derived from (21).

Pollutant	Specific emission g/kWh	Extra Emission from producing LER refrigerators kg/unit
SO_2	2.4	0.38
NO_x	1.0	0.16
CO	0.3	0.05
Particles	0.3	0.05

Table 11. The extra environmental cost in the form of air pollution from producing a LER refrigerator instead of a traditional one, K 215.

Like in most industrial activities the production of refrigerators also results in other environmental costs than those associated with energy, but we have not attempted to quantify those costs, since we assume the energy related costs to be dominant.

Environmental benefits in running LER

The annual energy savings, which is the main feature of LER, result in significant environmental benefits, which turn out to far outweigh the costs in producing them.

Table 12 shows the emission of air pollutant as well as the waste in the form of fly ashes (estimated from (24)) per kWh electricity consumed and the reductions achieved per year.

Pollutant and waste	Specific emission and waste (g/kWh)	Annual reduction per refrigerator (kg/year)	Annual reduction EEC (ton/year)
SO_2	5.5	0.9	90,000
NO_x	2.7	0.45	45,000
CO	0.2	0.03	3,000
Particles	0.7	0.10	10,000
Fly ashes	20	3.0	300,000
Highly radioactive waste	0.001	0.00003	3

Table 13. Reduction in air pollution and highly radioactive waste in EEC, if LER is introduced instead of the presently best refrigerators on the market. Compared to those in use today, the reductions will be roughly twice as high. See text to Table 12.

Most of the environmental benefits achieved through the use of low energy refrigerators instead of present ones can be achieved also by technical cleaning measures. For instance emission of SO_2 from coal power plants can be lowered by installing smoke cleaning equipment in the stacks. However, the two measures do not exclude each other and the environmental benefits achieved through a reduction in electricity consumption is more thorough, since it does not leave us with concentrated amounts of pollution materials such as piles of dust. Furthermore, the benefits are free of costs, since - as we have seen in the evaluation of economy - the extra production costs more than pay back in reduced energy bills.

CONCLUSION ON REFRIGERATOR

To conclude, the electricity consumption of LER2 (our low energy prototype refrigerator) in normal use did practically fulfill the target figure, which was 100 kWh/year. Since we found that the consumption of our reference refrigerator K215, (even including a reduction in normal use), was higher than the expected value of 245 kWh per year, the savings in absolute terms can be expected to be 150-175 kWh per year, if LER is introduced instead of the best on the market. This saving of around 160 kWh per year is more than the original target of 150 kWh per year. The savings to be achieved compared to the refrigerators presently in use is about twice as high.

The most direct consequence of gradually replacing the present stock of 2 millions refrigerators in Danish households with models like our LER2 instead of with the best on the market will be an annual saving of 320 millions kWh or 1.3% of Denmarks total electricity consumption. As coal dominates Danish power supply (app. 95 percent), the savings will with present supply systems reduce air pollution per year by around 2800 tons of sulfur dioxides and 1600 tons of nitrogen oxides. The amount of fly ashes produced per year at power plants will be down by 12000 tons. For EEC as a whole an estimated 16000 millions kWh could be saved per year, and air pollution would be down by 90,000 tons of SO_2 and 45,000 tons of NO_x, given the present electricity production distribution. Also, there would be 3 tons less high radioactive waste left. All the savings and environmental benefits is approximately twice as high if compared to the refrigeraters in use today.

As shown earlier the economy in switching to low energy refrigerators is very attractive with an annual 28% tax free return of the extra investment. From a Danish or a European point of view, the economy is even better, given that most of the costs associated with the electricity production is foreign import, while the extra investment on improving the refrigerators is mainly domestic wages etc.

Further work

Research on futher improvement of the efficiencies of refrigerators of various types continues at Physics Lab. III, and there are already indications that the electricity consumption can be reduced significantly below the 102 kWh per year achieved in this project. Also corresponding savings seem to be obtainable in freezers as well as in combined refrigerator-freezers with or without automatic defrosting.

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