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Impact Assessment of CFCs Retrofitting of Refrigeration Machines

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ABSTRACT: To fulfill the objectives of the Montreal Protocol, we have two main strategies to replace CFC refrigerants in refrigeration machines, i.e., 1. Conversion of the production of new refrigeration equipment to the application of environmentally benign substitutes, 2. Replacement of the refrigerant in existing refrigeration equipment under operation. In the paper the replacement of CFCs in existing equipment is discussed, especially with respect to domestic refrigerated appliances, commercial refrigeration equipment, and large capacity chillers for air conditioning. The technique applied to replace the CFCs is discussed, refrigerants applied to retrofit the machinery are evaluated, and a new technology to decompose the recovered CFCs is described. The environmental impact assessment methodology was applied to evaluate the proposed strategy.

1. INTRODUCTION

While the conversion of the production of new refrigeration equipment from using CFCs to environmentally benign substitutes has been financed for several years by means of the Montreal Protocol Funds, the replacement of CFCs in existing refrigeration equipment under operation has not yet started to be implemented. Why do we try to spend money to convert existing appliances? Both domestic and commercial as well as industrial refrigeration equipment are expensive and have a high life time especially in developing countries. The repair and the conversion of equipment is cheaper than to buy new appliances. Domestic refrigerators are repaired by means of recovery, recycling and retrofitting with CFC-12 until the application of this refrigerant in developing countries will be prohibited. The recycling technology of CFC-12 compared with retrofitting of refrigeration machines has already been studied, see [1]. It was found that retrofitting is the better technology with respect to the environmental impact. To replace the CFCs we have only one strategy: Recovery of CFCs, replacement by substitute refrigerants and decomposition of the recovered CFCs.

2. THE ASSESSMENT FRAMEWORK

The starting point of the assessment framework is the definition of boundaries for the assessment as follows: A. input, including material and energy, B. process stages, C. output, including final products, emissions, effluents and solid wastes products. Figure 1 shows the complexity of both alternative technologies [1].

2.1 Decomposition of CFCs

Different systems to decompose CFCs are available. The system shown in Figure 1 consists of a converter where natural gas and gaseous CFCs are burned together with air injected into the reaction area. A plasma of approximately 2000°C is generated that decomposes the

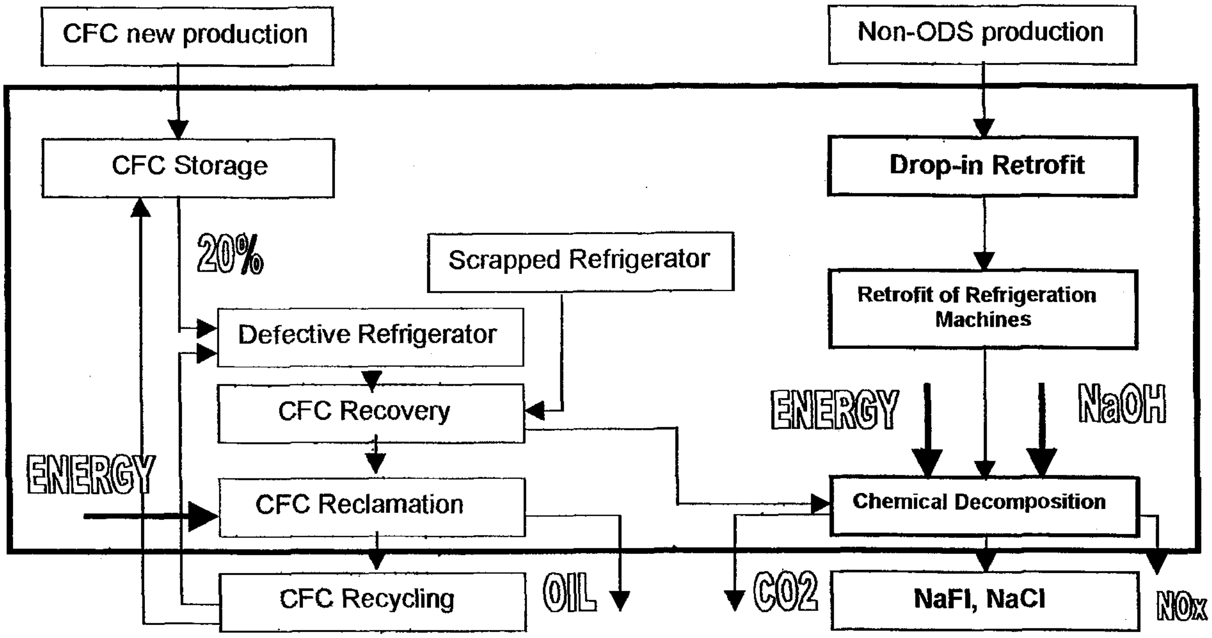


Figure 1: Scope of investigations and definition of system boundaries [1]

molecules of fluorinated and chlorinated hydrocarbons. The plasma is led into a so-called 'quench' where a 50% concentrated water-caustic soda (NaOH) solution circulates. Natural gas, compressed air, water and NaOH are the only raw materials required to operate the chemical decomposer. Depending on the chemical structure of CFCs the outcome is crystallized NaFl and NaCl or NaBr in a salty form. The exhaust gases are purified and following a catalytic oxidation only small quantities of CO_2 are released to the atmosphere. NaFl and NaBr are valuable raw materials that allow the installation to be operated economically. From an input of 180g of CFC one gets a mixture of 450g NaFl and NaCl, to which $0.0015m^3$ natural gases have to be added as fuel.

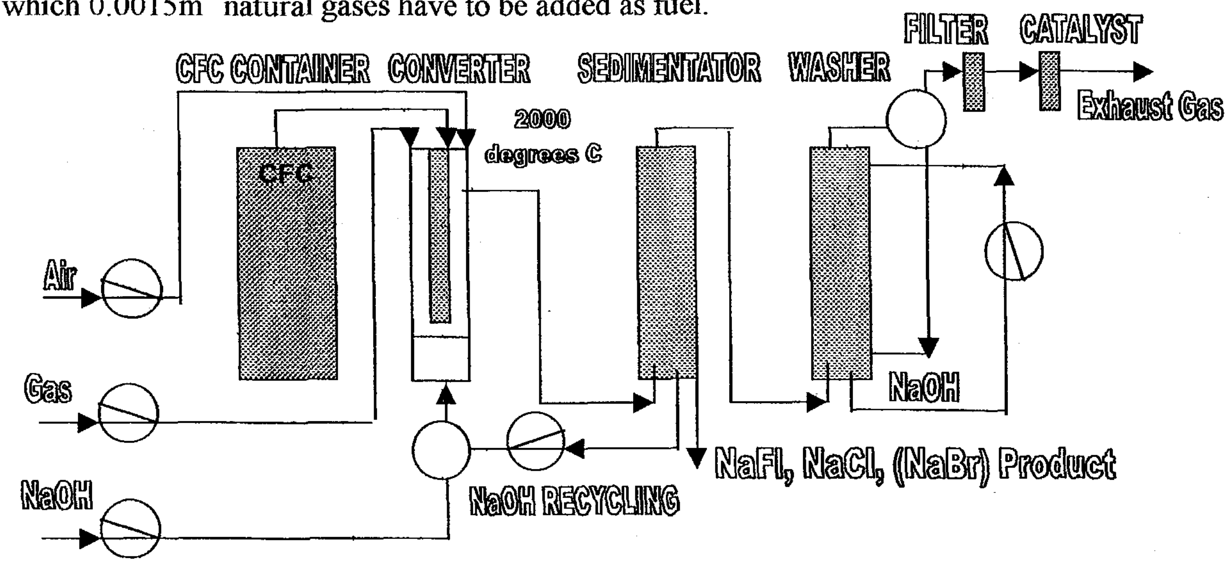


Figure 2: Process Chart of the Chemical Decomposer

2.2 Comments on the Recycling of CFCs

From the above analysis [1] it should be stressed that CFC-12 recycling only plays a marginal role in reducing the use of virgin CFC-12. Although recycling the CFC-12 is more economical but technically not easy to handle, it is not recommended because of its environmentally unfriendly processing. The most promising prospect for reducing the application of recycled CFC-12 is the retrofitting technology of existing refrigeration equipment and the decomposition of the recovered CFCs.

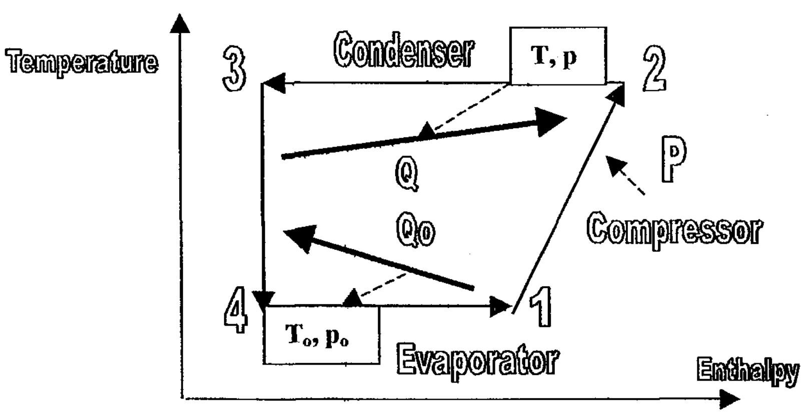
3. RETROFITTING OF EXISTING INSTALLATIONS

3.1 Analysis of the Conditions

Retrofitting of existing refrigeration machines is a complex task. These machines have been optimized for the conditions under which they are operated. If a refrigeration machine will be retrofitted with a substitute refrigerant the following criteria have to be studied:

-the thermodynamic working condition of the system and design parameters,
-the condition of the system (existing leaks or malfunctions),
-the convertibility of the system,
-the replacement of components,
-the regulations for safety and technical approval,
-the selection of a suitable refrigerant and lubricant,
-the chemical stability of refrigerant and oil with materials.

In Figure 3, a simple model is demonstrating the thermodynamic working conditions of a refrigeration system under operation [9].



$$Q = m_w \, cp_w \, \Delta T_w$$
$$Q = k_c \, A_c \, \Delta Tm_c$$
$$Q = Qo + P$$
$$Qo = m_R \, \Delta h$$
$$Qo = k_e \, A_e \, \Delta Tm_e$$
$$Qo = m_c \, cp_c \, \Delta T_c$$

Figure 3: Simplyfied model of a refrigeration machine

A. Thermodynamic Working Conditions and Design Parameters

Figure 3 shows the basic thermodynamic equations and design parameters that describe the detailed processes occuring in a refrigeration cycle. We start the analysis with the refrigeration compressor. The basic equation is

$$P = m_R \, (h_2 - h_1) = V \, \varrho_1/\lambda \, (h_2 - h_1) \qquad (1)$$

where V is the swept volume [m^3/h], ϱ_1 the gas density [kg/m^3], λ the compressor efficiency [-], and (h_2 - h_1) the enthalpy difference [kJ/kg] required to compress the refrigerant from the evaporation pressure p_o to the condensing pressure p. From the installation to be retrofitted we know the refrigeration capacity at the condensing temperature T and the evaporation temperature To. We know as well the swept volume V of the compressor. With the appropriate data of the new refrigerant we may estimate the data of the enthalpy and gas density. Based on equation (1) we obtain the refrigeration capacity to be expected. In case the refrigeration capacity is too small, we have to replace the existing compressor by selecting the next larger one in size. If the existing compressor is older then 15 years, the new compressor selected will compensate for the somewhat higher power consumed by the new compressor. The strategy explained above can only be applied for piston-type compressors. Compact refrigeration units with centrifugal compressors require a special treatment that will be explained later.

Following the compressor we have to consider the evaporator side of the refrigeration machine. The equation (2) describes the thermodynamic behaviour of the evaporator and the medium to be cooled:

$$Qo = m_R\,(h_1 - h_4) = k_e\ A_e\ \Delta Tm_e = m_c\ cp_c\ \Delta T_c \qquad (2)$$

The mean logarithmic temperature difference is defined as

$$\Delta Tm = \Delta T_2 - \Delta T_1/[\ln(\Delta T_2/\Delta T_1)] \qquad (3)$$

where ΔT_2 is the difference in temperature between the evaporation temperature and the temperature of the medium to be cooled at the evaporator inlet, and ΔT_1 the appropriate temperature difference at the evaporator outlet. The difference (h_1 - h_4) [kJ/kg] is the heat capacity generated at the evaporator, k_e the overall heat transfer coefficient of the evaporator [kJ/(m^2 h K)], ΔTm_e the mean logarithmic temperature difference [K] as defined by equation (3), m_c the mass flow rate of the medium to be cooled [kg/h], cp_c the specific heat capacity of the medium to be cooled [kJ/(kg K)], and $\Delta T_c = Tc_{in} - Tc_{out}$ is the temperature difference [K] of the medium to be cooled. It will of course be difficult to estimate the new overall heat transfer coefficient of the new refrigerant. From the ratio of the appropriate value of the heat transfer coefficient α_1 of the refrigerant to be replaced, and α_2 the refrigerant to be charged, we can estimate the possible modification of the overall heat transfer coefficient by means of the Nusselt-number: $Nu = \alpha d/\lambda$. The geometry of the evaporator will not be changed. Consequently, we obtain

$$\alpha_2 = \alpha_1\ \lambda_2/\lambda_1 \qquad (4)$$

In case of an evaporator the overall heat transfer coefficient is dominated by the lowest value of the heat transfer coefficient from the air to the evaporator surface. Approximately, we may estimate

$$1/k = 1/\alpha_{outside} + 1/\alpha_{inside} \qquad (5)$$

where $\alpha_{inside} = \alpha_2$. Using equation (1), we may check the evaporation temperature to be obtained with the new refrigerant.

$$a = \exp\,[A_e\ k_e/(m_c\ cp_c)]$$

$$To_{new} = Tc_{in} - Tc_{out}\ a/(1\ - a) \qquad (6)$$

where Tc_{in} and Tc_{out} are the required temperatures of the medium to be cooled [°C], A_e the heat transfer area of the evaporator [m^2], k_e the overall heat transfer coefficient [kJ/(m^2 h K)] of the evaporator following conversion to the new refrigerant. If the estimated evaporation temperature To_{new} deviates from the temperature To that is required, the value To of the starting point has to be changed until both values To and To_{new} are in correspondence.

Finally, we have to estimate the influence of the refrigerant on the behavior of the condenser. Equation (7) describes the appropriate thermodynamic conditions:

$$Q = Qo + P = m_R (h_2 - h_3) = k_c A_c \Delta Tm_c = m_w \; cp_w \Delta T_w \qquad (7)$$

The conditions are comparable with the evaporator. The difference $(h_2 - h_3)$ [kJ/kg] is the condensing heat, k_e the overall heat transfer coefficient of the condenser [kJ/(m^2 h K)], ΔTm_e the mean logarithmic temperature difference considering condensing temperature and the temperatures of the cooling medium [K], A_c the condenser area [m^2], m_c the mass flow rate of the cooling medium [kg/h], cp_c the specific heat capacity of the cooling medium[kJ/(kg K)], and ΔT_c the temperature difference of the cooling medium [K]. By means of equations (4) and (5) we may estimate the overall heat transfer coefficient of the condenser following replacement of the original refrigerant. This will allow to decide whether the new refrigerant can be accepted as a replacement that will ensure a proper working of the converted refrigeration machine.

B. Condition of the System (existing leaks or malfunctions)

Statement: If a system is working properly and not leaking there should not be a reason to replace the refrigerant charged into the system.
Before starting with the retrofitting of the new refrigerant all leaks and malfunctions have to be replaced.

C. Convertibility of the System

As already mentioned under paragraph A. compact refrigeration units equipped with a centrifugal compressor cannot easily be converted. This kind of refrigeration machines has been designed for the specific application. If a new refrigerant will be taken into consideration the centrifugal compressor especially the impeller, the gear, and the electric motor have to be redesigned by the manufacturing company.

D. Replacement of Components

Components, especially the compressor (if necessary), the capillary tube (domestic refrigerator), the filter dryer have to be replaced. The expansion valve, thermostats, etc. have to be checked for their compatibility and replaced as well if necessary.

E. Regulations for Safety and Technical Approval

These regulations have thoroughly to be considered especially in case where flammable refrigerants will be applied as replacements for originally non-flammable refrigerants.

F. Selection of a Suitable Refrigerant and Lubricant

The refrigerant will be selected following the thermodynamic analysis described under position A. In most cases a new lubricant has to be selected as well. The new lubricant (in many cases ester oil) that has to be used may cause problems during retrofitting. Supplier of refrigerant and oil have developed a procedure how the retrofitting has to be implemented.

G. Chemical stability of refrigerant and oil with materials
The existing installation has to be checked in close cooperation with the original manufacturer whether the new refrigerant and oil is compatible with all materials used in the existing plant.

Some software offered by manufacturers of refrigerants and compressors can be very helpful to estimate the behavior of equipment following the retrofitting with the substitute.

3.2 Implementation of Retrofitting

Before starting the implementation of retrofitting for each individual design of refrigeration machine available, a project document has to be elaborated considering the individual steps described under position A. to G. in the previous paragraph. The specific refrigeration machines require different technologies in case of implementation. In any case we recommend a close cooperation with the appropriate manufacturer of the equipment.

3.2.1 Domestic Appliances

The refrigeration cycle of domestic refrigerators and domestic freezers is carried out fully hermetically. Now valves are available allowing an simple access to the refrigerant. In case of opening the refrigeration cycle so-called piercing valves are used to make an opening into the pipe of the refrigerant cycle. This valve is then used to recover the original refrigerant and to retrofit the substitute. As the retrofitting is carried out at customers premises the technician needs all the equipment required to implement the retrofitting, e.g., the recovery unit, a cylinder for recovered CFC, another cylinder for the refrigerant to be retrofitted, a scale to measure the quantity of refrigerant, a leak detector, a thermometer, hoses, pressure gauges for the refrigerants, etc. The piercing valve has to be replaced following completion and the hole in the pipe has to be closed.

3.2.2 Commercial Equipment

The procedure of retrofitting is carried in the place where the equipment is installed. Mostly the time during the night is used for retrofitting to avoid any disturbance of the official working hours. The service technicians, which have to repair commercial refrigeration machines require the same equipment as described before with the peculiarity that commercial refrigeration machinery is equipped with valves and receivers for the liquid refrigerant allowing an easy access to the refrigerant. The retrofitting of commercial refrigeration equipment is often accompanied with the replacement of the original lubricant. Consequently, a comprehensive procedure must be implemented to clean the refrigeration cycle from traces of the original mineral oil.

3.2.3 Chillers for air conditioning

Chillers installed in air conditioning installations are equipped with centrifugal compressors exclusively designed for the required refrigeration capacity, the applied refrigerant and the existing temperatures. In many cases CFC-11 or CFC-12 are used. CFC-11 that is a low pressure refrigerant has limited prospects for retrofitting because open-type compressors are used designed for the low pressure conditions while the compressors designed for the refrigerant CFC-12 can be retrofitted under the precondition that the system has to be redesigned by the original manufacturer.

4. REFRIGERANTS TO RETROFIT EXISTING INSTALLATIONS

We have now some substitutes for existing installations available. Some of them are considered as drop-in refrigerants, the most important of which are natural refrigerants. The acceptance of these substitutes is growing despite of their flammability. See Table 1.

5. DISCUSSION

From the above analysis, it should be stressed that CFC-12 recycling only plays a marginal role in reducing the use of virgin CFC-12. The most promising prospect for reducing the application of CFC-12 and R502 is the retrofitting technology of refrigeration equipment under operation and the decomposition of the recovered CFCs. Refrigerants that are considered to be appropriate substitutes especially in the domestic sector, the commercial and industrial refrigeration sector are available. Natural refrigerants are important because they reduce the depletion of the Ozone Layer and reduce the impact on the Greenhouse Effect. The mixture of R290/600a applied to retrofit domestic appliances is most promising because the originally used mineral oil is compatible with the new refrigerant. The refrigerant R290/600a as a retrofitting substitute allows the operation of the old refrigerator without any modification [5, 6, 7, 8]. The mixture of R290/600a has the advantage that less than half of the original quantity of CFC-12 is required due to its much lower density, which reduces the risk of accidents with the flammable substitute. A drawback results from the temperature glide, which avoids that some application of refrigerators (e.g., two evaporators in serial connection) cannot be retrofitted this way.

Table 1: Properties of some selected substitutes to replace CFCs (CFC-12, R502)

Substance	ODP (R11=1)	GWP (CO_2=1)	Oil	Flammable	Boiling temp.	Application	Temp. Glide
CFC-12	**1**	**8,100**	**mineral**	**no**	**-30**	**Domestic refrigeration, centrifugal chiller, industrial refrigeration**	**no**
HFC-134a	0	0	synthetic	no	-26.1	Domestic refrigeration, centrifugal chiller, industrial refrigeration	no
R290/600a	0	0	mineral	yes	-30	Domestic refrigeration	8K
R401A	0.037	1,100	synthetic	no	-33	Industrial refrigeration	<4K
R409A	0.048	1,400	synthetic	no	-34	Industrial refrigeration	<6K
R502	**0.23**	**5,500**	**mineral**	**no**	**-45.6**	**Commercial refrigeration**	**no**
R404a	0	3,700	synthetic	no	-47	Commercial refrigeration	<0.5
R507	0	3,800	synthetic	no	-47	Commercial refrigeration	no

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