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Future scenarios for household refrigerator/freezer

This appendix presents the assumptions and calculation used to identify the future energy consumptions of the following types of household appliances:

- Combined upright fridge/freezer
- Upright freezer
- Upright refrigerator
- Chest freezer
- Upright refrigerator with a small freezer box

Assumptions

The following assumptions have been made:

- The COP that has been used for the cooling system is based on a 40 % Carnot efficiency. This has been assumed on the basis of a modern compressor is installed in the cooling system.
- It is assumed that due to research and development in the near future the Carnot efficiency of the cooling system will steadily increase from 40 % to 65 % by the year 2050.
- It is assumed that the insulation within the doors and cabinets comprise of 0% VIP (Vacuum insulated panel) panels and slowly increased to 55 % by the year 2050. It is assumed that only a 55 % substitution of the currently used polyurethane is plausible due to the weakening of the structural integrity of the units, meaning that a fridge/freezer will not be able to support itself if the VIP panels are not surrounded with polyurethane foam.
- Due to the relatively high cost of the VIP panels, it is assumed that in the future, the manufacturers will be given economic or political incentives to develop more energy efficient product and therefor implement VIP.
- The insulation thickness of the doors and cabinets are based on measurements of products that represent the average of that type of unit.

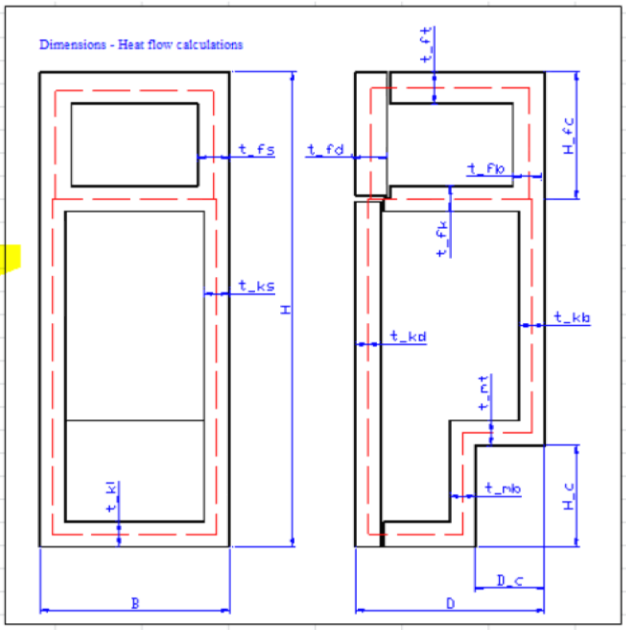
Calculation method

The calculations have been performed using programs[1] that have been specially developed by Danish Technological Institute. The programs calculate the total heat loss through the doors and the walls of the cabinet of a fridge/freezer unit. By modifying several of the input parameters e.g. height of the unit, width, insulation type/composition, COP of the cooling system etc… a yearly energy consumption can be calculated.

The following calculations are based on a combined upright refrigerator/freezer unit, but the procedure is the same for the other four scenarios. Different aspects of the program will be reviewed as well as explained to give a better overview of the calculation behind the programming.

Geometry

Width, outer	B	m	0,520
Hight, outer	H	m	1,860
Dept, outer	D	m	0,580
Hight of compressor room, outer	H_co		0,245
Depth of compressor room, outer	D_co		0,145
Hight form top to mid floor freezer/cooler	H_fc	m	1,035
Netto volumen, cooler	V_f	ltr	189
Netto volumen, freezer	V_k	ltr	91
Netto volumen, total	V_net	ltr	280



The blue text is the different input for the external dimensions of the unit. The highlighted yellow fields are the volumes of the cooler and freezer compartment of the unit. The volumes of the compartments are calculated among other things from input parameters of the insulation/door thickness.

[1] Beregning_af_boks_med_VIP(1) and Beregning_af_skab_med_VIP(1)

	Wall sum(s) m	VIP s_vip m	VIP Area p_VIP %	A_heat m2	ISO s_is m	r_A %	A_is m2	A_vip m2	U_is W/m2K	U_vip W/m2K	U W/m2K	Heat loss PHI W
Top of cooler	*0,080*	*0,000*	*80*	0,252	0,078	6,5	0,050	0,201	0,25	0,25	0,25	2,8
Sides in cooler	*0,045*	*0,000*	*80*	1,055	0,043	27,3	0,211	0,844	0,43	0,43	0,43	20,5
Door in cooler	*0,055*	*0,000*	*80*	0,473	0,053	12,2	0,095	0,378	0,36	0,36	0,36	7,6
Back wall in cooler	*0,045*	*0,000*	*80*	0,473	0,043	12,2	0,095	0,378	0,43	0,43	0,43	9,2
Floor in cooler (top of freezer)	*0,080*	*0,000*	*80*	0,235	0,078	6,1	0,047	0,188	0,25	0,25	0,25	1,2
Sum cooler			**80,0**	**2,252**		**58,2**	**0,450**	**1,801**			**0,41**	**41,3**
Sides of freezer	*0,080*	*0,000*	*80*	0,706	0,078	18,3	0,141	0,565	0,25	0,25	0,25	3,5
Bottom in freezer	*0,080*	*0,000*	*80*	0,154	0,078	4,0	0,031	0,123	0,25	0,25	0,25	0,8
Door in freezer	*0,090*	*0,000*	*80*	0,345	0,088	8,9	0,069	0,276	0,22	0,22	0,22	1,5
Back wall in freezer	*0,080*	*0,000*	*80*	0,238	0,078	6,1	0,048	0,190	0,25	0,25	0,25	1,2
Vertical wall, compressor room	*0,080*	*0,000*	*80*	0,108	0,078	2,8	0,022	0,086	0,25	0,25	0,25	0,5
Horisontal wall, compressor room	*0,080*	*0,000*	*80*	0,064	0,078	1,7	0,013	0,051	0,25	0,25	0,25	0,3
Floor in cooler (top of freezer)	*0,080*	*0,000*	*80*	0,235	0,078	6,1	0,047	0,188	0,25	0,25	0,25	-1,2
Sum Cooler			**80,0**	**1,615**		**41,8**	**0,323**	**1,292**			**0,21**	**6,7**
Total				3,87				3,09				48,0

The illustration above shows some of the input fields for the thickness of the doors and cabinet. By modifying the percentage of the VIP installed in the unit, a heat loss and thereby a cooling load can be found and later used to calculate the energy consumption.

Ambient, wall and insulation			
Temperature, ambient	t_a	°C	25
Temperature, air in freezer	t_f	°C	-20
Tempereture, cooler	t_k	°C	5
Outer wall thicknes	s_o	m	*0,001*
Outer wall heat coeff.	k_o	W/mK	*0,3*
Inner wall thicknes	s_i	m	*0,001*
Inner wall heat coeff.	k_i	W/mK	*0,3*
PUR heat coeff.	k_pur	W/mK	*0,021*
VIP heat coeff.	k_VIP	W/mK	*0,0045*
Heat transmission coeff., internal	alfa_i	W/m2K	*7,5*
Heat transmission coeff., external	alfa_u	W/m2K	*7,5*

The highlighted fields show the assumed inside and ambient temperature, while the other input fields show some of the material properties of the VIP panel as well as polyurethane.

Power consumption				
Compressor type	type	-	xxx	
Temperature difference, evaporator	dt_evp	K	7	
Evaporating temperature, ON	t_e	°C		-27
Temperature difference, condensor	dt_cond	K	7	
Condensing temperature	t_c	°C		32
Cooling load, compressor ON	PHI_e	W	52,6	
COP	COP	-	1,67	
Duty cycle	duty	%		102
Power, compressor, ON	P_ON	W		32,0
Power, average	P	W		32,0
Energy consumption	E	kWh/d		0,769
		kWh/y		281

The highlighted fields show the yearly energy consumption of the unit as well as the COP for the cooling system.

The COP that has been used as input is derived from the previously assumed Carnot efficiency of 40 %.

Based on Carnot theorem we can calculate the theoretical maximum COP for the system from the assumed operating temperatures, where the operating temperatures are indicated by the arrow in the illustration above.

$$COP_{carnot} = \frac{Coldest\ temperature}{Hottest\ temperature - Coldest\ temperature} = \frac{(273-27)K}{(273+32)K-(273-27)K}$$

$$COP_{carnot} = 4{,}17$$

The COP for the system is then isolated in the following equation:

$$\eta_{Carnot} = 0{,}40 = \frac{COP}{COP_{carnot}}$$

$$COP = 0{,}4 * COP_{carnot} = 0{,}4 * 4{,}17 = 1{,}67$$

The same procedure is done when we look at the reduction in energy consumption for a steadily increasing Carnot efficiency.

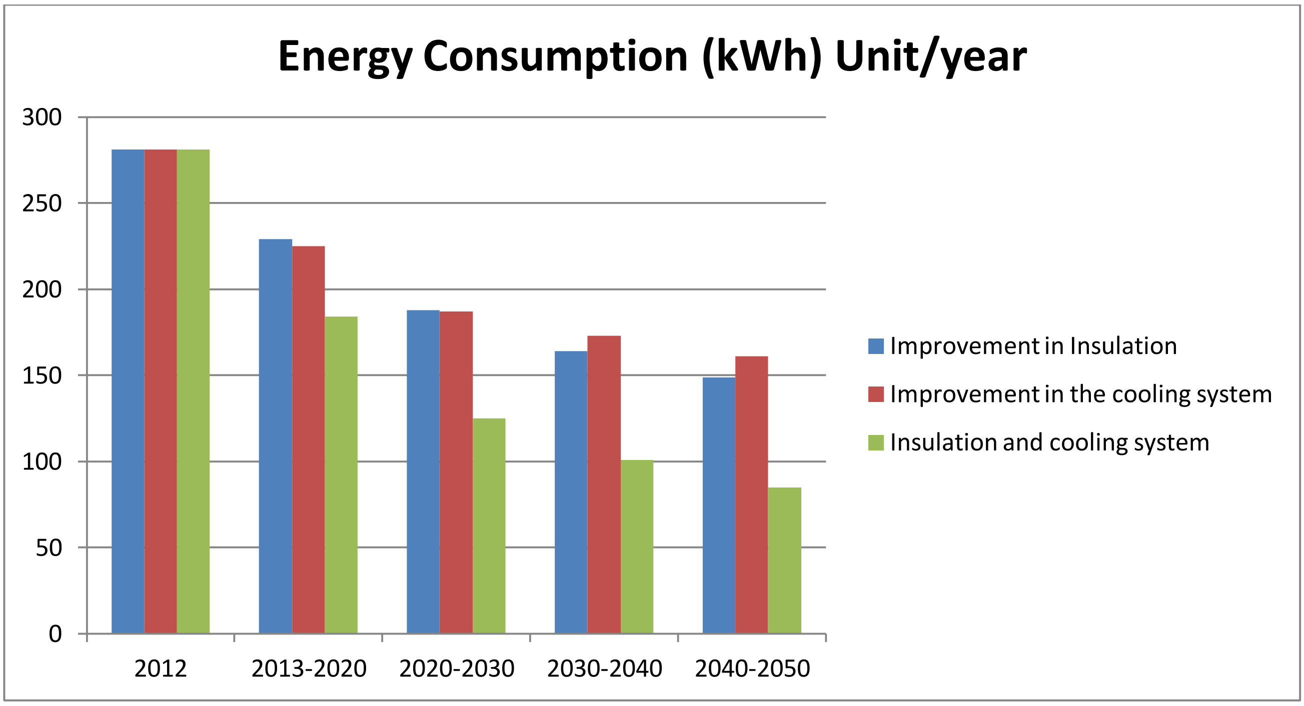
Do note that when this calculation is done for the upright refrigerator scenario, that the evaporating temperature is much lower due to the similarly lower operating temperatures.

Results

The following graphs and tables are the results of the different simulations that have been performed with the program, where we have looked at the energy savings through insulation and improvement in the cooling system separately and together.

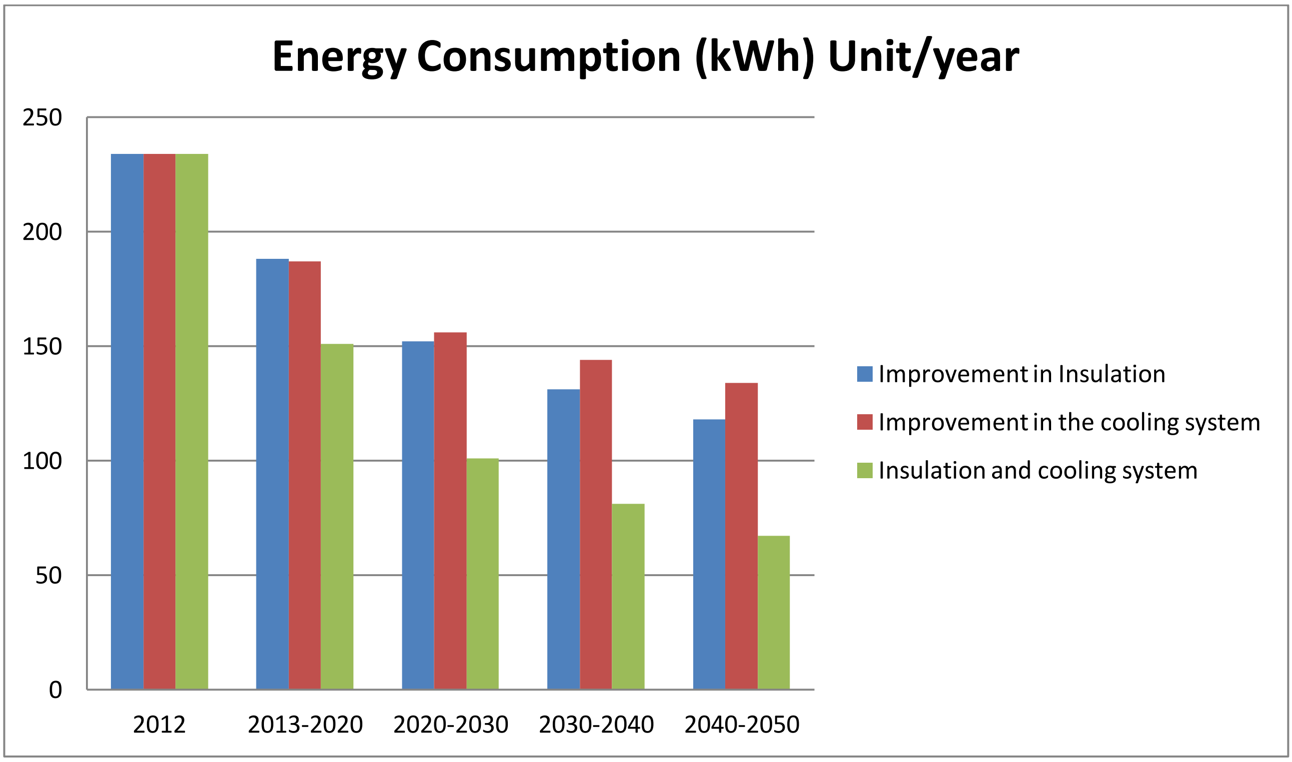
Combined upright fridge/freezer

Improvement in Insulation					
Percent VIP composition	0%	10%	25%	40%	55%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	281	229	188	164	149
Improvement in the cooling system					
Carnot efficiency	40%	50%	60%	65%	70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	281	225	187	173	161
Insulation + Cooling system					
Percent VIP composition/Carnot efficiency	0%/40%	10%/50%	25%/60%	40%/65%	55%/70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	281	184	125	101	85



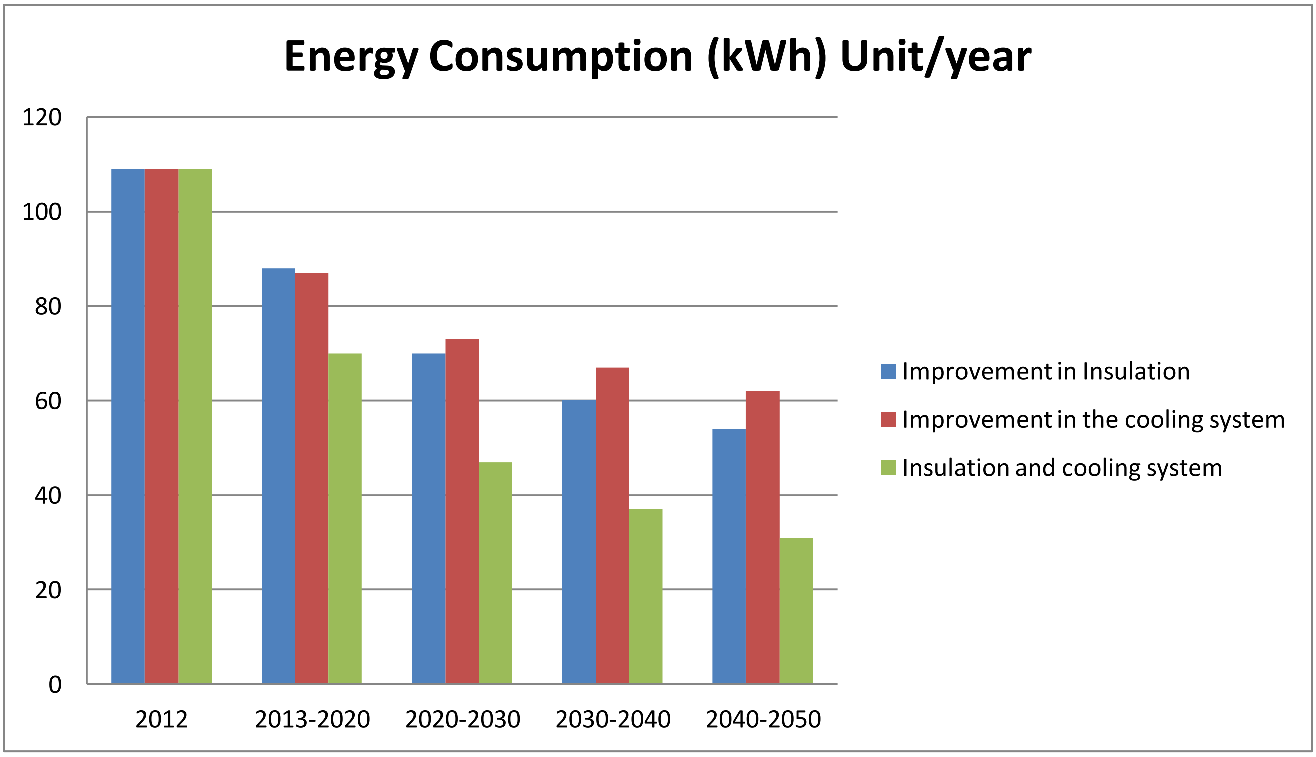
Upright freezer

Improvement in Insulation					
Percent VIP composition	0%	10%	25%	40%	55%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	234	188	152	131	118
Improvement in the cooling system					
Carnot efficiency	40%	50%	60%	65%	70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	234	187	156	144	134
Insulation + Cooling system					
Percent VIP composition/Carnot efficiency	0%/40%	10%/50%	25%/60%	40%/65%	55%/70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	234	151	101	81	67



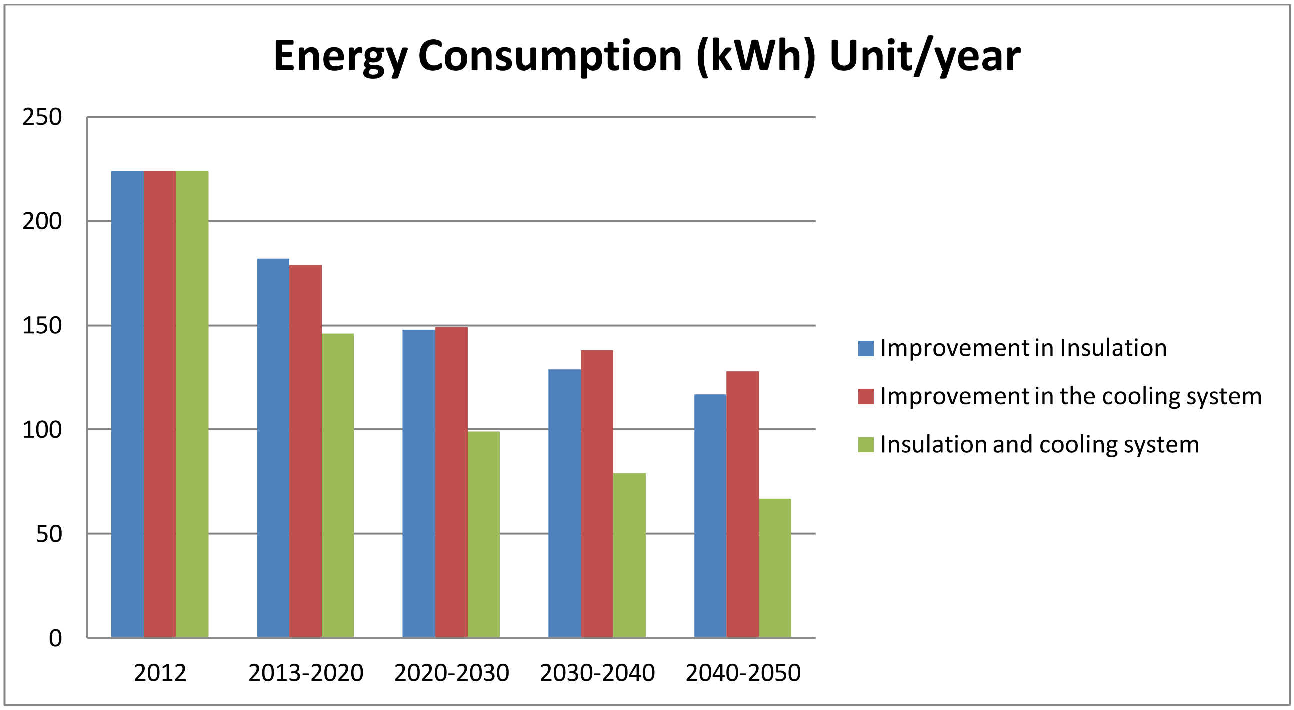
Upright refrigerator

Improvement in Insulation					
Percent VIP composition	0%	10%	25%	40%	55%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	109	88	70	60	54
Improvement in the cooling system					
Carnot efficiency	40%	50%	60%	65%	70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	109	87	73	67	62
Insulation + Cooling system					
Percent VIP composition/Carnot efficiency	0%/40%	10%/50%	25%/60%	40%/65%	55%/70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	109	70	47	37	31



Chest freezer

Improvement in Insulation					
Percent VIP composition	0%	10%	25%	40%	55%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	224	182	148	129	117
Improvement in the cooling system					
Carnot efficiency	40%	50%	60%	65%	70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	224	179	149	138	128
Insulation + Cooling system					
Percent VIP composition/Carnot efficiency	0%/40%	10%/50%	25%/60%	40%/65%	55%/70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	224	146	99	79	67



Upright refrigerator with a small freezer box

Improvement in Insulation					
Percent VIP composition	0%	10%	25%	40%	55%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	211	172	141	124	113
Improvement in the cooling system					
Carnot efficiency	40%	50%	60%	65%	70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	211	169	140	130	120
Insulation + Cooling system					
Percent VIP composition/Carnot efficiency	0%/40%	10%/50%	25%/60%	40%/65%	55%/70%
Year	2012	2013-2020	2020-2030	2030-2040	2040-2050
Consumption per year (kWh)	211	138	94	76	64