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Experimental Investigation of the Use of Propane for Domestic Refrigerator with Lower Displacement Compressor

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ABSTRACT

The performance of R290 has been investigated experimentally to replace R12 in a domestic refrigerator with 3.16 cc displacement compressor. A210 litres refrigerator intended to operate with R12 is used in our study with a lower displacement compressor and longer capillary. The consumed energy, temperatures and pressures at salient points the refrigerator circuit and also temperatures at various compartments in the refrigerator are recorded. The experiments are conducted are no load performance test and ice making test with R290 as well as R12 at a surrounding temperature of 30°C. As per our results R290 is the most viable alternative to replace R12 from the view point of energy conservation without the necessity of changing lubricating oil and drier used with R12 but with a slightly lower capacity. The flammability nature can be ignored as the amount of refrigerant used is very low.

1. INTRODUCTION

Refrigeration technology plays an important role in the conservation of food and life-saving drugs in particular in the safety and health of individuals. Refrigeration technology is also used to provide comfort through air-conditioning systems and for industrial processes [1]. Montreal protocall was signed by 32 nations in 1987 under UNEP for the protection of ozone layer under UNEP. India is one of the members of Monteal protocol since 1992. The Kyoto protocol was signed in 1997 to control green house gases and refrigerants having higher GWP. In the knowledge of the CFC hazard and the Montreal and Kyoto protocols, the Generation-3 refrigerants must be considered [2] -HCs & Natural refrigerants. CFC-12 is outdated when introduced to the refrigerator industry and was replaced by the intermediate refrigerant HFC-134a (Generation-2). However, the Generation-2 refrigerants also need to be phased out by 2020; in this context, it is necessary to analyze the prospects of Generation-3 refrigerants and to retrofit or replace the existing HFC-134a refrigerator inventories. A number of refrigerants, pure as well as blends have been considered all over the world as retrofit refrigerants. Attempts have also been made to search for short term alternatives which require minimal changes in the system. Hydrocarbon refrigerants are compatible with zero ODP, negligible GWP and commonly used mineral lubricating oil. These refrigerants' primary drawback is that they are extremely flammable. Hydrocarbon refrigerants have elevated latent vaporization heat compared to R12 and low density make these refrigerants appealing due to low load despite their flammability [3].

A number of scientists proposed the applications of hydrocarbons as substitutes to existing refrigerants in household refrigerators. James and Missenden [4] investigated the performance of Propane in small sized domestic refrigerators. The results showed that Propane is a viable alternative to R12 without any modification. Richardson and Butterworth [5] studied a domestic refrigerator working with Propane and concluded that performance of Propane was better than of R12. Experiments have been conducted with propane and propane/isobutane mixtures in a domestic refrigerator and the results revealed that obtained COP was higher than that of R12. Wongwises and Chimers [6] investigated the use of Propane in a 239 litres capacity refrigerator and the results indicated that with Propane the refrigerator consumed least amount of energy per day. Due to higher volumetric refrigeration capacity use of compressor with lower displacement is required to substitute Propane. The properties of a of HCs using SRK EoS were estimated by Parashurama et al. [7] in his earlier work, and the properties obtained are well within permissible limits. Performance was determined and conducted computer simulation to screen hydrocarbons as alternative refrigerants to substitute R12 in medium-sized domestic refrigerator. It was discovered that R270 and DME were appropriate as suitable drop in candidates and R290 and R1270 with lower displacement compressor.

All hydrocarbons except for Propyne and Propadiene are compatible with Copper [8]. Therefore, Propane does not need to alter the refrigerator building material. With standard mineral oil, all hydrocarbons are miscible and have excellent lubrication characteristics. Another benefit of hydrocarbons is that there is no admission of moist air due to favorable evaporator pressure. Studies by Gur-saran. Mathur and Jung [9] show that the heat transfer features for hydrocarbons in liquid as well as gaseous states are considerably greater than R12 and R134a. R290 is therefore a feasible option from a heat transfer point of perspective. R134a is currently being used as an option to R12.Its energy efficiency is low, GWP is high and immiscible with mineral oil. Hence the problem is not resolved and it has to be replaced in accordance with F-gas regulation [10]. In his prior work, Parashurama et al. [11] estimated thermodynamic properties of HCs, HFCs and Fluroethers using SRK EOS, screened and proposed R270, R152a and

R161 as solutions to R134a with the same compressor and R290 and R1270 with reduced compressor displacement. Isobutane is another leading alternative refrigerant to R12 FOR new manufacturing of domestic and commercial refrigeration appliances. HC-600ahas an excellent compatibility with commonly used mineral oils and other materials used in refrigeration systems. Similar manufacturing practices used in case of CFC-12 can be followed except that some safety precautions are to be taken as it is a flammable refrigerant. This refrigerant has a higher normal boiling point and needs about 80% higher compressor same cooling effect because of higher VRC. This results in higher cost of conversion. Therefore this option is not practicable [12].

From previous studies it is observed that Propane was tested with the same compressor that is used for R12 (4.5 cc) and there was no power savings. Because of higher volumetric refrigeration capacity than R12 a lower displacement compressor is sufficient for R290. In open literature the investigation of use of Propane using lower displacement compressor for medium sized domestic refrigerator is not available. In the present study, a 3.16 cc hermetic compressor was used to obtain the performance of R290 from the view point of energy conservation.

2. THEORETICAL THERMODYNAMIC ANALYSIS

The description of Figure 1 is given as follows:

1.Superheated vapour entering the compressor.
2. Superheated vapour after compression.
3. Superheated vapour entering condenser.
4.Saturated vapour in condenser.
5.Saturated liquid in condenser.
6. Sub cooled liquid in condenser.
7. Sub cooled liquid entering capillary.
8. Refrigerant leaving capillary in Wet condition.

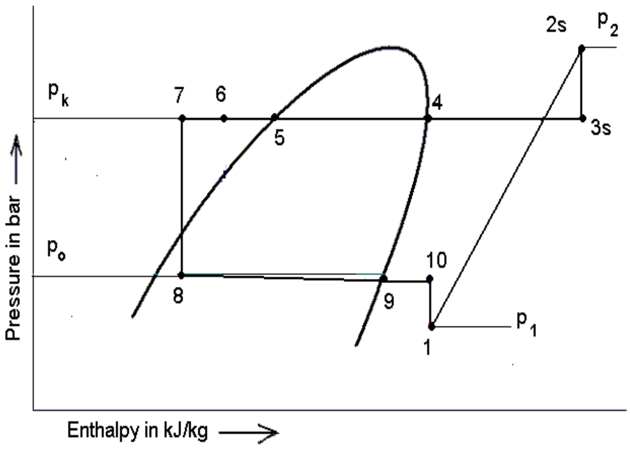

Figure 1. Actual vapor compression cycle for theoretical thermodynamic analysis

2.1 Specifications of the refrigerator used for the analysis [13]

Compressor: The compressor Capacity is 89 W, the displacement volume is 4.49 cc, suction temperature is 32°C, allowable discharge temperature is 130°C &slip is 5%.

Condenser: Condensing temperature is 55°C and the Condenser is Natural convection cooling type.

Expansion device: The expansion device is capillary of length 3 m, inner diameter is 0.79 mm, and outer diameter is 1.8 mm.

Evaporator: Evaporator inlet temperature is –25°C, with degree of superheat at outlet 0°C & cooling capacity is 89 W.

Regenerator: The regenerator used is tube-in-tube type & having the outside tube dimensions, inner diameter 4.58 mm, outer diameter 6.0 mm, length 1.25 m. inside tube dimensions are those of the capillary.

Theoretical assessment for refrigerants R12 and its alternative R 290 was performed by Parashurama et al. [4]. Table 1 summarizes the outcomes of the study. R290 and R12 performance assessment was performed using simulation to calculate parameters such as cooling capacity, mass flow rate, pressure ratio, condenser duty, discharge temperature, starting torque and cop. The simulation findings show that R290 performs better with a greater COP value and needs a reduced compressor displacement (2.43 cc) with a slightly reduced motor rating.

Table 1. Results of theoretical analysis

Refrigerant	R290	R12
Mass flow rate (Kg/sec) ($\times 10^4$)	0.289	0.722
Compressor Power input (W)	40.32	43.94
Condenser duty (W)	137.83	153.4
Piston displacement(cc)	2.43	4.6
Starting Torque (N-m)	2.16	2.77
COP	1.84	1.76
Discharge Temperature(°C)	125	135
Isentropic Index	1.124	1.137
Capillary bore,d (m)	0.00066	0.00079
Capillary length,L(m)	4.178	2.29

3. SAFETY ASPECTS OF HYDROCARBON REFRIGERANTS

Hydrocarbons are flammable and it is necessary to implement safety measures during servicing or retrofitting. in refrigeration systems. There are a number of schools of thought on this issue. These can be classified into two. According to the first the amounts of refrigerants used in the system is so small that it does not pose any safety risk. The electrical components used in the refrigerator should be replaced by non-sparking electrical components as per safety standards. Another school of thought is not to use hydrocarbons in refrigerators.

A considerable amount of efforts has been made on these issues. Agarwal, Kessler and Gartshore have developed [14] a manual for safe conversion and servicing of refrigerators. The safety issues have been addressed. The manual has adopted a practical approach, based on various safety standards available and guidelines have been prepared how to make the appliance safe.

The safety issues are almost important. These have been adequately addressed in the manual for safe conversion and servicing of refrigerators. The approach is practical. It has been proposed to eliminate the sparking points and components. This has been achieved by replacing the standard the standard electric components by non-sparking sealed or PTC based electric components so that appliance is safe as no ignition can take place from itself. According to safety standards the maximum amount of flammable refrigerant used should be below 150 g. Hence this is not an issue in our case as the amount of flammable refrigerant,R12 used is 55g.

4. EXPERIMENTAL SETUP

The test chamber is provided with a small wooden chamber for the circulation of air. It is also provided with temperature sensors to measure the simulation chamber temperature; relative humidity sensor, heater coils, steam-injecting nozzles, which are connected to steam raiser kept outside the chambers and split air conditioner is provided for chamber to simulate the required weather conditions with help of condenser heat rejection to test chamber. The line diagram of the experimental setup constructed is shown in Figure 2. Two pressure gauges are fitted to record the pressures at compressor inlet and outlet. Thermocouples were provided at salient points of the refrigerator to measure temperatures simultaneously using data acquisition. The instrumentation includes 3 no of Pressure Gauges, 11 number of Thermocouples, one Digital thermometer and one Clamp meter. All thermocouple extension wires from refrigerator and electric cable for supply have been taken out and connected to the data logger panel. The Table 2 shows the details of the instrumentation used and the uncertainty.

Table 2. Details of measuring instruments

Instruments	Range	Uncertainy
Pressure Gauges	0 to 10.34 & 0 to 20.69 bar	±0.345 bar (5 Psi)
Thermocouples	----	±0.1ºC
Digital thermometer	-50 to 500ºC	±0.1ºC
Clamp meter	0 to 10 amps 0to 1000 volts	±0.1Amps ± 1 V

The L.G. make 210 liters refrigerator is used for the experiment. The propane having 98.5% purity with freezing point of -44.10°C and NBP -42°C refrigerant was procured from Baruka Gases Ltd, Bangalore. The computer with the help of data acquisition modules i.e. ADAM-4018 analog input module and ADAM-4520 isolated RS 422 converter was used [15] to acquire thermocouple output.

5. EXPERIMENTATION AND PERFORMANCE ANALYSIS

The experimentation was conducted for R12 refrigerant and the hydrocarbon Propane. The initial experiments were conducted according to the theoretically calculated capillary length as given in the Table 1. The experimentation has been done to optimize capillary lengths for different refrigerants for no load performance test. The ice-making tests were also conducted according to the IS standards.

Numbers of experiments were conducted for various tests as mentioned above to get the precise data from the test rig. Certain results are discarded due to optimizing the mean compartment temperature to 7°C by adjusting the thermostatic knob, power failure, failure to maintain the condition as mentioned in IS standard etc.

Initially, leakage tests were conducted with the existing setup and it was found that there was leakage in condenser and after replacing the condenser again leakage test was conducted and it was found that there was leakage in evaporator. The evaporator has been replaced and leakage test conducted. No of leakage tests conducted are given in Table 3. Initial trials were conducted with R12 to become familiar with the experimentation. Tests were conducted with 3.16 cc displacement Compressor with various capillary lengths to obtain the pull down and with a capillary length of 5.9 m; we have got pull down and required results.

Table 3. List of leakage tests

Compressor Displacement	Refrigerant	No of Leakage tests
3.16	R290	4
4.49	R12	4

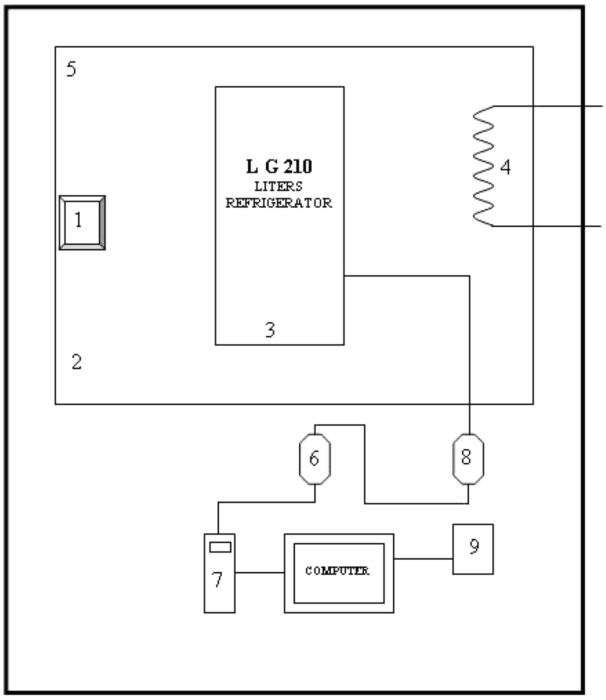

Figure 2. Lay out of experimental set up and simulation room

In Figure 2 the points correspond to the following elemental components [16].

1. Air Conditioner
2. Humidification Sensor
3. Test Refrigerator
4. Heating Coil
5. Simulation Room Temperature
6. Thermocouple Wire
7. Analog to Digital Converter
8. RS 485 to RS 232 Converter
9. DC Power Supply
10. Control Panel

Experiments conducted in accordance with IS standards [17] are leakage test, No Load Performance test, Ice Making Test, Rated Energy Consumption test. Pull down time, the time required pulling down to the mean cabinet air temperature from 43°C to 7°C without the thermostat in the circuit. For ice making test after stable operating conditions were obtained, following pull-down period, a quantity of 0.7 liters of water at ambient condition in two standard ice trays was kept in the freezer, and the time was noted. If ice was not formed during 3 hours of operation, the system operation was to be continued.

Certain results are discarded due to optimizing the mean compartment temperature to 7°C by adjusting the thermostatic knob, power failure, failure to maintain the condition as mentioned in Indian standard etc. Temperatures at Compressor inlet, Evaporator inlet, Condenser outlet, Evaporator outlet, Compressor outlet, Third Compartment, second compartment, Freezer compartment are recorded using the thermocouples and suction pressure and discharge pressure are also recorded using pressure gauges. The electrical energy consumed by the compressor was measured by a Clamp-on Wattmeter with 0.01 KWh resolution. Leakage tests were conducted using Nitrogen and soap bubble.

The optimization of charge and capillary length has been done by cut and try method for minimum power consumption. The amount of Refrigerant R12 charged into the system is 100 g and that of R290 is 55 g. Capillary length works out to be 5.9 and 3 metres for R290 and R12 respectively. Total 25 experiments were conducted on no load performance analysis and 22 ice making tests were conducted. Only valid experiments were considered for the performance analysis. Tests with R290 were conducted with 3.16 cc displacement Compressor with a capillary length of 5.9 m and for no load performance test, after pull down period, the system was run up to 6 hours and refrigerator was run for three months. For ice making tests after pull down period, the system was run up to a period of 3 hours. The refrigerator was run for three months to confirm the results obtained. The ice making test for R 290 with capillary length of 5.9 metre and for R12 with capillary length of 3.0 meter was continued up to 3 hours after pull down. Experiments are conducted till the steady state conditions are attained.The refriigerator was run upto 6 hours after pull down to reach steady state conditions.

Table 4. No load energy consumption test and ice making test results

Refrigerant	R290	R12
Capillary length (m)	5.95	3.0
Suction Pressure	2.895	1.768
Discharge Pressure	15.855	13.840
Discharge Temperture (°C)	66.4	70.2
Pull down time (minutes)	111	110
Pull down energy consumption (kWh)	0.1369	0.153
Energy consumption (kWh/day)	1.329	1.710
Ice making time (minutes)	173	143
COP_{act}	1.77	1.72
η_{refri}	55.81	41.2
I (w)	56.14	12.96

6. RESULTS AND DISCUSION

Table 1 lists the values of performance parameters for R12 and its alternative R290. The value of Pressure ratio for R290 appears to be lower than that of R12; this implicates the requirement of lower displacement compressor. Hence higher boiling refrigerant R290 requires lower rating of the motor than that of R12 as seen from Table 2. The energy consumption appears to be lower than that of R12.

From Table 2 it can be observed that due to high Pressure ratio the volumetric efficiency of R290 works out to be slightly lower. The displacement volumes of R12 and R290 are calculated using the above values of the volumetric efficiencies. As the volumetric refrigeration capacity is higher than that of R12, R290 requires lower displacement compared to R12 as seen from Table 2. The discharge temperatures of R290 is lower than that of R12. Higher the discharge temperature, higher is the winding temperature. Since the amount of charge required for Hydrocarbons is very small & far well within safety standards, viz., 55g only there is no risk of fire hazard. Hence R290 compressor runs smooth and use of R290 is economical.

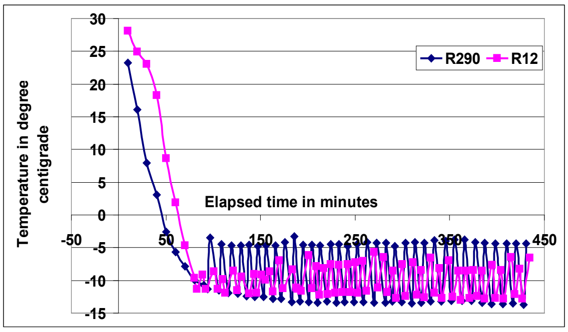

Figure 3. Temperature profiles of refrigerants in Freezer during no load performance test

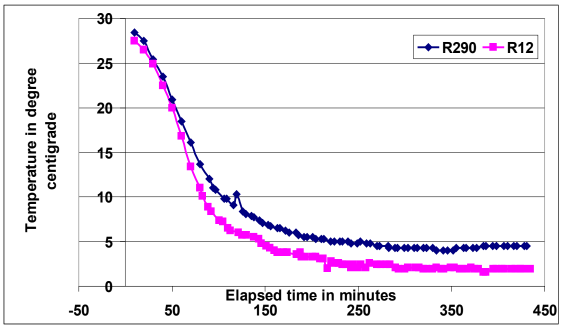

Figure 4. Temperature profiles of refrigerants in upper compartment during no load performance test

The theoretical analysis indicates that COP of R290 is higher than that of R12. Also condenser heat rejection rate is lower than that of R12 and indicates that condenser need not be oversized. In case of R290 the mass flow rate is quite lower than that of R12 and the pressure ratio is higher. Therefore increased length of capillary is needed. If R12 compressor is employed for R290 there is no problem as far as Starting Torque is concerned. In this experimental study, R12 and R290 were tested under the same operating conditions using a domestic refrigerator designed to work with R12. For testing R290 the original compressor was replaced by a 3.16 cc displacement. The original lubricating oil and drier were not changed. The variation of temperatures in the compartments of the refrigerator during no load pull down test and ice making test are shown in Figures 3 to 8. The various performance parameters such as pull down time, ice making time, energy consumption are noted as tabulated in Table 4. As seen in Table 4, pull down time for R290 is 14.6% higher than that of R12, ice making time is 20.9% higher than that of R12 and energy consumption is 27.6% lower than that of R12 and the maximum compressor discharge temperature is 2.2°C lower than R12. Pull-down tests, ice making tests and temperature profiles indicate that refrigerator with R290 has comparable capacity than that of R12 as seen from Figure 3 to

8. The long term performance is understudy.

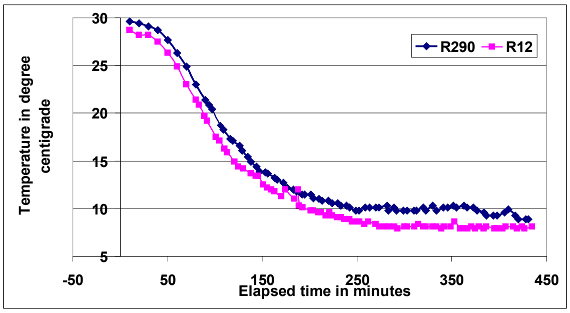

Figure 5. Temperature profiles of refrigerants in lower compartment during no load performance test

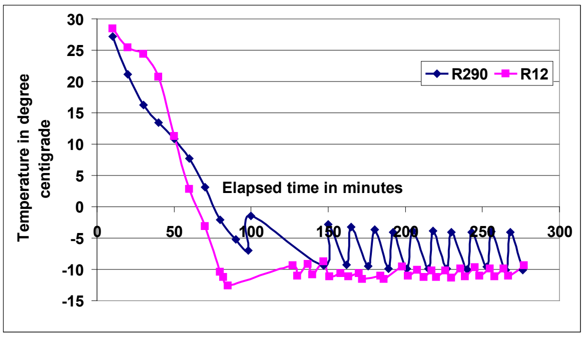

Figure 6. Temperature profiles of refrigerants in Freezer during ice making test

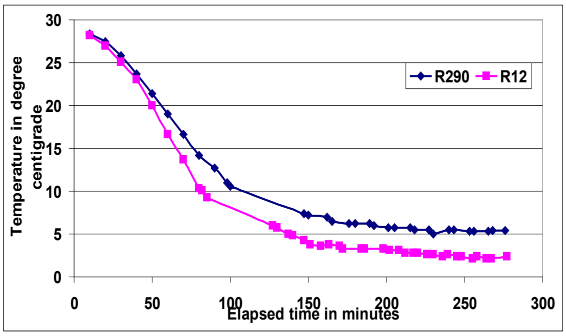

Figure 7. Temperature profiles of refrigerants in upper compartment during ice making test

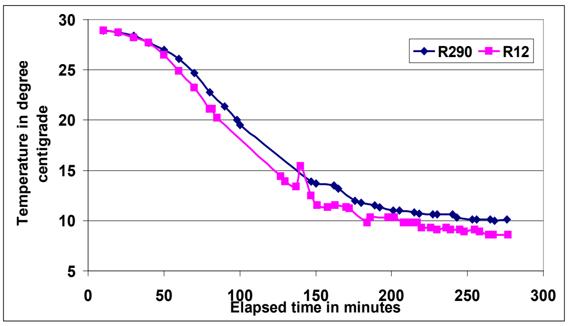

Figure 8. Temperature profiles of refrigerants in lower compartment during ice making test

7. CONCLUSION

Based on the theoretical and experimental analysis the following conclusions can be drawn. The theoretical analysis indicates that COP of R290 is higher than that of R12. Heat rejected in the condenser is lower in case of R290 and the size of the condenser remains same. In case of R290 the mass flow rate is lower than that of R12 and the pressure ratio is higher. Therefore increased length of capillary is needed. Energy, Pull down and ice making tests were performed to compare the performance of the refrigerants. Propane showed 27.6% increase in energy efficiency when compared with R12.The amount of charge for Propane decreased by 40% and the length of capillary used was 5.9 m. The compressor discharge temperature with Propane is lower than that with R12 which is indeed desirable. Hence it could improve compressor life. Pull-down tests and ice making tests indicate that R290 has comparable capacity than that of R12.

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NOMENCLATURE AND ABBREVIATIONS

COP	Coefficient of Performance
d	Capillary bore (m)
h	Enthalpy (kJ/kg).
L	Capillary length (m)
m	Mass flow Rate (kg/s)
NBP	Normal Boiling Point (°C)
P	Pressure (bar).
ΔP	Pressure drop (bar)
Q	Cooling effect. (W) Heat rejection (W)
T	Temperature (°C), Torque (N-m)
v	Specific Volume (m^3/kg)
V	Volume (cc)
VRC	Volumetric Refrigeration Capacity(kJ/m^3)
W	Work input (W)

Subscript

e	evaporator
fg	vaporization
i	inlet
isen	isentropic
k	condenser
o	outlet
p	piston displacement
stg	starting
1, 2, 2s, etc.,	state points