The potential application of residential solar thermal cooling in the UK and the role of thermal energy storage technologies.

E Ampatzi and I Knight
Welsh School of Architecture, UK

ABSTRACT

As the UK Building Regulations demand better insulated and more airtight new buildings, a potential cooling requirement is emerging in new build dwellings in the UK, leading to an increase in the market for domestic air conditioning systems in this country.
At the same time, current strategies at a European and National level are starting to focus on the use of renewable and low carbon energy sources, aiming at energy security and reduction of carbon emissions.
Solar thermal cooling in small scale residential applications is of particular interest due to the major electrical energy supply problems experienced in many countries related to the demand for cooling in summer. Only recently have such small scale systems become commercially available and it is still a relatively expensive technology. The performance of these systems depends strongly on the local climate, the COP of the cooling system and the holistic design of the plant and buildings. Either absorption refrigeration or desiccant cooling can be used in solar cooling applications.
Solar cooling is normally designed to cover a certain percentage of the demand (30%-60%) and an auxiliary fossil fuelled system is therefore required to drive the Thermally Activated Cooling Systems (TACS) the periods when there is insufficient solar energy.
This paper explores the potential cooling demand in a dwelling in the UK and the use of Thermal Energy Storage (TES) systems to increase the solar fraction available. The paper uses the ECOTECT (see Ecotect) building modelling software to model a particular dwelling, drawn from generic regional UK housing stock information (Rhodes et al., 2007) as a Case Study to illustrate the paper's aims. A scenario to simulate realistic hourly patterns of occupancy and internal gains due to appliances and lighting is described. The cooling requirement and the collector area required to meet this demand are calculated. The role of the TES in relation to the solar fraction of the system is investigated. The limitations of the software used for this simulation are also discussed along with the reliability of the results.

1. INTRODUCTION

1.1 Thermal Energy Storage (TES) systems

A wide variety of TES technologies have been developed over the years (Hadorn, 2005). Although useful applications of these technologies in fossil fuelled driven systems for cooling have been discussed (MacCracken, 2003 and MacCracken 2004) there is a great potential to use these technologies to deal with intermittent energy sources such as Solar.
This paper will examine the role of TES in Residential Solar Thermal Cooling systems. A different approach for the TES component is needed for cooling only applications, compared to applications which cover also space and DHW heating. In summer, solar availability will almost match with the cooling demand, while in winter a different kind of thermal energy storage solution would be needed.

1.2 Solar Thermal applications in the UK

Solar Thermal systems have only recently become popular in the UK. Research shows that in the year 2000 only 151,000 m^2 of water collectors (both flat plate and evacuated tube) were in operation in the UK (Weiss, 2003). This equates to <3 m^2 of collector area per 1,000 inhabitants, which is significantly lower than countries like Greece (264 m^2), Austria (198 m^2), Denmark (46 m^2), Switzerland (37 m^2) and Germany (34 m^2).
There is a false impression, shared even amongst architects and designers, that there is insufficient solar energy in the UK to achieve solar fractions which would contribute significant energy savings and carbon reductions, within economically feasible solutions.

1.3 Cooling demand in UK dwellings

Whilst Climate Change is in the headlines as the cause of higher temperatures, in the UK Residential sector the high levels of insulation and air-tight construction methods required by the UK Building Regulations from 2000 onwards are also partially responsible for the increasing cooling requirement in this country. In addition, increasing internal gains are appearing due to the expanding number of appliances used by the occupants on a daily basis. Small scale thermally-driven Cooling Systems such as absorption chillers are starting to penetrate the European market. As shown later in this paper the use of such systems would mean that the potential Solar Thermal energy demand distribution over the year at an annual level would be more constant due to the increased cooling demand in summer. This would mean a reduction of the risk of stagnation for a solar system during the Summer months.

2. THE CASE STUDY building

The dwelling modelled is a typical semi-detached house built according to Part L of the 2000 Building Regulations and located in Cardiff, UK. Internal gains are modelled assuming a working family of 4, with average hourly DHW and electrical load profiles based on European residential DHW and electrical profiles obtained from IEA Annex 42 (Knight et al, 2007).
Using this information, the total cooling demand of the dwelling is estimated using ECOTECT's own internal calculation engine, based on the CIBSE admittance method (CIBSE, 2006).
The available solar energy is also estimated using ECOTECT for this location and weather data, and is compared with the 30 years average data for Cardiff found in related work (Page et al, 1983). The role of the TES component is explained in a solar cooling-only application.

2.1 Geometry and U-values
The Case Study dwelling represents one of the building classes tested in the STACS project (Rhodes et al, 2007). The total internal floor area of the dwelling is 77.3 m^2.
Figure 1 shows the Case Study model built in ECOTECT and the maximum size of the collector area. Table 1 lists the material properties of the model fabric (which correspond to the UK 2000 Part L standards).

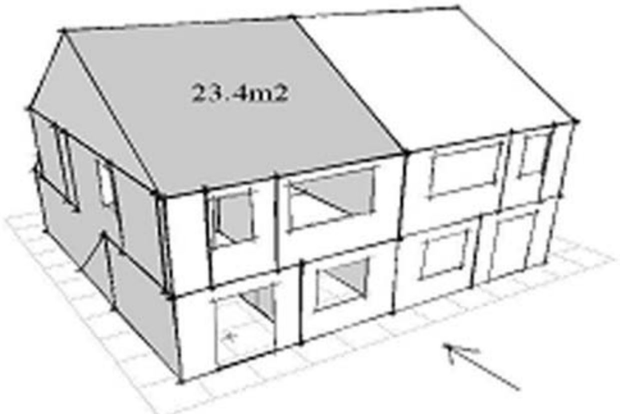

Figure 1 - Case Study building from South

Table 1 - Construction materials and U-values for Case Study building.

Building Component	Layers	U-value
Wall	• 12mm plasterboard (internal) • 100mm dense concrete blocks • 50mm Celotex (rigid foam insulation) in 100mm cavity 100mm brick (external)	0.40
Roof (ventilated)	• Concrete tiles • Felt/underlay	5.89
Ceiling	• 125mm WarmCell (blown cellulose Insulation) • 12mm plasterboard	0.36
Glazing	• 24mm sealed double glazed in uPVC	1.06
Ground Floor	• 5mm wood laminate • 5mm polyurethane foam sheet • 50mm concrete screed • 100mm concrete slab • 50mm 50mm Celotex • DPM • 25mm sand blinding • Compacted hardcore	0.38
First Floor	• 5mm wool / polyester carpet • 10mm rubber underlay • 18mm chipboard • 150mm void • 12mm plasterboard	1.51
Internal Partitions	• 12mm plasterboard • Steel Stud frame with 80mm void • 30mm acoustic insulation in the void • 12mm plasterboard	0.71

The building is divided into 13 thermal zones: entrance hall, (ground floor:) kitchen, dining, lounge, WC, store A, (1st floor:) bedroom 1, bedroom 2, bedroom 3, bathroom, store B, boiler closet, and roof zone.

2.2 Average DHW and electrical demands
The average DHW and electrical demands caused by occupants, appliances and lighting were simulated based on the profiles presented in Annex 42 of the International Energy Agency, Energy Conservation in Buildings and Community Systems Programme (Knight et al, 2007). These profiles, which have been proposed in the Annex 42 project as "a good first estimate of domestic electrical energy consumption profiles" that could apply in most European countries, are based on UK domestic profiles monitored by EETS Ltd and the Welsh School of Architecture (Kreutzer et al, 2006).
The Annex 42 report suggests 102 litres per household per day as an average daily DHW consumption, based on a 45°C rise, for the UK. (Knight et al, 2007). There-

fore the energy required for the daily draw off of DHW for this model is 5.32 kWh. For the purposes of this study, this demand is simply added to the daily space heating and cooling load (it is not included as hourly data in the ECOTECT model) as the focus of this paper is on the cooling demand only and not on the total thermal demand.

For estimating the internal heat gains due to electricity use, the average European domestic electrical energy consumption model, provided by the Annex, is composed of six profiles according to 3 typical seasons of the year (winter, summer and shoulder season) and two typical days of the week (weekday and weekend). The data is in 5-min intervals and the unit is Watts. For the ECOTECT model average hourly values are required and so the 6 typical days/ profiles are averaged accordingly. To apportion the total heat output in the different zones of the building the information provided by the Canadian analysis in the same study is used (Knight et al, 2007). From this data we calculated the portion of the total annual load used by each of the 8 major appliances (Table 2) and applied that to the European profiles. It was also assumed that the 6 major appliances (dishwasher, clothes washer, tumble dryer, range, fridge and freezer) are all located in the kitchen zone. This accounts for around 50% of the total annual demand and therefore it is important that this load was correctly located within the kitchen zone.

The peak heat output from these kitchen appliances was found therefore to be around 46 W/m^2 between 18:00 to 19:00 on a winter weekday. Figure 2 shows the daily profile for the kitchen at this time of year which was used in the model.

Table 2 – Contribution (%) of the appliances in the model. Derived from Annex 42 work.

appliance	appl/dwel (Canadian)	kWh/y (Canadian)	%
1. Refrigerator	1	801.00	11.06
2. Freezer	1	614.00	8.48
3. Dishwasher	1	94.00	1.30
4. Clothes washer	1	99.00	1.37
5. Clothes dryer	1	1284.00	17.74
6. Range	1	769.00	10.62
7. Other appliances	8.98	2465.00	34.05
8. Lighting (/m2)	141 m2	1113.12	15.38
Kitchen (1-6)	6 in total	3661.00	50.57
Remaining (7-8)	unknown	3578.12	49.43
Total		7239.12	100

The remaining loads account for the other 50% of the total and are due to lighting and other small appliances. This remaining load was distributed evenly in all the 13 zones (including the kitchen). The peak rate for these other loads was found to be 4.6 W/ m2 i.e. 10% of the kitchen appliance gains. These gains are also shown in Figure 2.

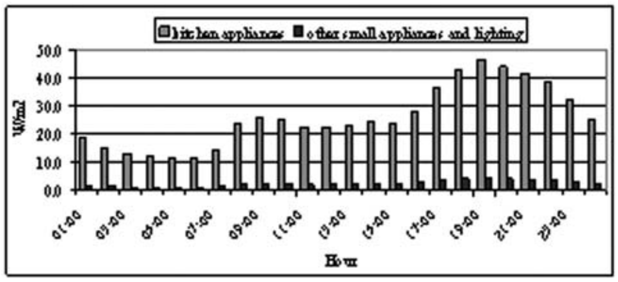

Figure 2 - Winter weekday profile of the kitchen appliance and other electrical gains used in the model.

Figure 3 presents the Annex 42 schedules used over the year to apportion these gains in the ECOTECT model. The labels “wiwd” and “wiwe” represent the profiles for the winter weekday and weekend respectively, “sswd” and “sswe” are the shoulder season weekday and weekend respectively and “suwd” and “suwe” are the summer weekday and weekend.

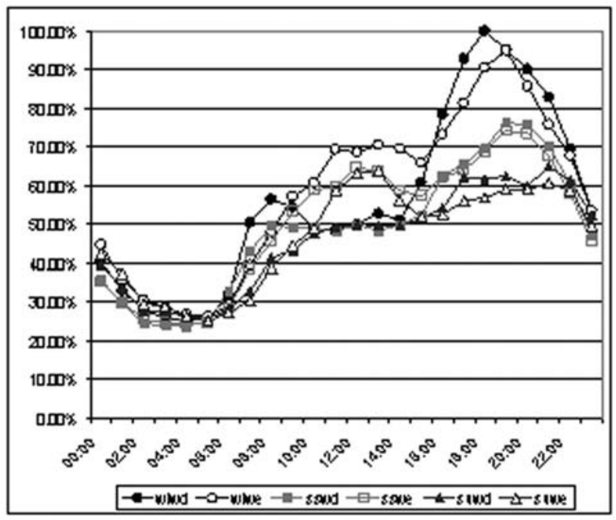

Figure 3. The six typical day profiles used to schedule the electrical gains over the year

2.3 Occupancy and Comfort requirements

The house is assumed to be occupied by 4 inhabitants (3 bedrooms). For the sleeping period, taken to be 23:00 to 07:00, a schedule was assigned in the 3 bedrooms for the whole of the year.

For the remaining occupancy of the house the following rationale was used. A typical weekday is considered as occupants using the house during the periods 07:00 to 08:00 and 17:00 to 23:00. For the weekend it is assumed that the house is occupied during the day, 07:00 to 23:00. The gains from occupancy *during the day period* were evenly distributed over the whole living area (74.9 m^2 is the total living area, excluding the 3 store zones). The activity used was the same for all the zones and it was considered to be an average of "walking". Table 3 shows the heat gains corresponding to each zone due to this distribution of the occupancy.

Table 3- Heat gains during the day period assigned to each zone.

Zone name	Area (m^2)	Heat output (W)
Kitchen	7.59	32
Dining	8.33	36
Lounge	15.96	68
WC	2.18	9
Bed 1	11.17	48
Bathroom	4.33	18
Bed 3	4.93	21
Bed 2	10.47	45
Entrance	9.96	43
Total	74,92	320

The recommended temperature for every zone was set in Winter and Summer so that the cooling/heating load needed to maintain thermal comfort within the space can be calculated. The CIBSE recommended temperatures for different rooms in dwellings were used (CIBSE, 2006).

For the ventilation rates CIBSE recommended values were used (CIBSE, 2006). The building was assumed to be relatively airtight and a background infiltration rate of 0.25 ac/h was therefore applied. For the cooking period, taken to be 07:00 to 08:00 and 17:00 to 19:00 (for the weekend two more hours are added from 13:00 to 15:00), the kitchen is ventilated with 10.8 ACH. The bathroom and WC peak ventilation rate (5 ACH) applies only between 07:00 – 08:00 and 20:00 – 21:00. For the rest of the time the ventilation rate for these 3 zones is similar to the one used for the other zones (0.50 ACH).

Table 4 shows the thermostat settings and ventilation rates used.

Table 4- Thermostat values per room according to the CIBSE comfort standards. ACH assigned to zones.

Room type	Comfort Temp ^{o}C	Ventilation rate ACH
Kitchen	17-23	0.25 + 10.8 (peak)
Dining/ lounge	22-25	0.25 + 0.50
Bedrooms	17-25	0.25 + 0.50
Entrance/halls	19-25	0.25 + 0.50
WC/ bathroom	19-21	0.25 + 5 (peak)

2.4 Weather data.

The weather data used for the calculation in ECOTECT is the one provided with the software and it is in .wea format. It is actual data measured during 1 year in Cardiff. Figure 4 shows the difference between calculations using 1 year and 30 year average data. The values represent the incident solar energy on a $10m^2$ surface orientated towards south and tilted for 45^o in Cardiff calculated with the ECOTECT weather data and from average weather data of the years 1941-70 (Page et al, 1983). The latter work does not provide complete information in order to compose a specific year weather data for our calculations, and the comparison is used to illustrate the potential error of these calculations.

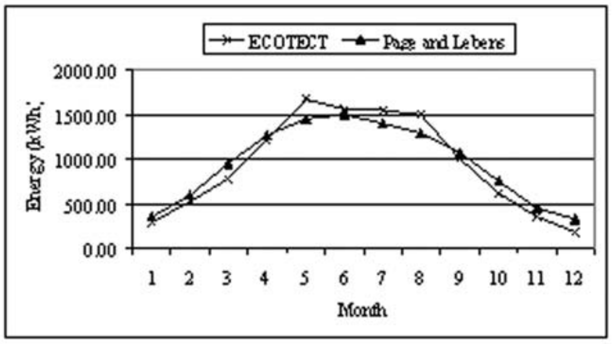

Figure 4. Comparison between Incident (direct and diffuse) solar energy curves (10m2 collector, 45° tilt South) calculated with the ECOTECT data and with 30 year average values given by Page and Lebens (Page et al, 1983).

3. RESULTS

3.1 Availability of solar energy and total energy demand. Figure 5 shows the monthly incident solar energy on different sizes of solar collectors facing South and with a 45^o tilt, based on weather data collected during a 30-year period (Page et al., 1986) for the city of Cardiff.

These figures are compared to the total monthly energy demand (including domestic hot water preparation, space heating and cooling) calculated in ECOTECT with the model described above. To calculate these loads it is assumed that a Full Air Conditioning system with 95% efficiency is operated to provide heating or cooling every time the indoor air temperature is not within the thermostat range.

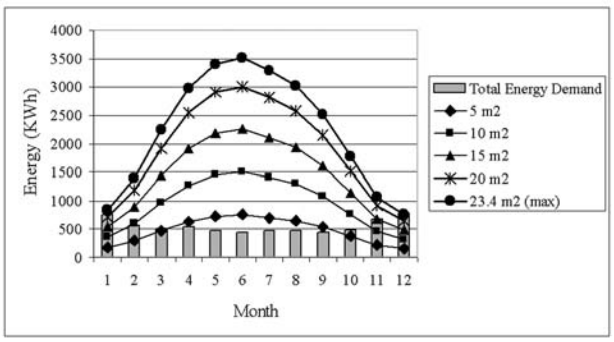

Figure 5. Incident solar energy on various collectors' sizes from Page and Lebens (South, 45°) and total monthly energy demand (DHW, Space heating and Cooling) of the reference dwelling (Ecotect Weather data). Location: Cardiff.

Figure 5 is presented here to illustrate the availability of solar energy compared to a realistic energy load. The maximum potential collector area is 23.4 as this is the total area of the south part of the tilted roof in the reference building. It is apparent from the graph that the energy falling on that roof on a yearly basis would be more than adequate to meet all the thermal demands if an efficient TES was also integrated into the system. The annual cooling demand calculated for this model is 1472 kWh (as opposed to 3226 kWh annual heating demand) and it peaks on the 20th of May. That peak, which is recorded a Sunday (high internal gains due to occupancy, appliances and lighting) coincides with the incident solar energy peak (Figures 4 and 6) recorded in the weather data used by ECOTECT (1 year measured weather data is used for the simulations). If no air conditioning system is used then the highest temperature calculated is 36.6°C for the kitchen zone on the 9th of August at 17:00. This reinforces the belief that there is a demand for cooling in UK housing.

3.2 Intermittency of solar energy: The need for a TES component

In a cooling only plant, the focus is on the period between May and September. In Figure 6 the thermal energy required to meet the cooling load is contrasted to the collector yield. Using Figure 5 the collector area chosen is 9 m^2 (3 units of 3 m^2 each).

Figure 6 appears to show that this area of collector would be sufficient for this demand. The collector yield is estimated by simply multiplying the incident solar energy values on a 9m^2 collector (South, 45^o tilt) by the efficiency of the collector (0.81, Thermomax).

The thermal energy required for the cooling load is calculated by dividing the cooling demand, calculated from the model, by the COP of the chiller (0.70, Rotartica), assuming that the output of the chiller unit used is sufficient to cover the whole cooling demand. In reality the COP of the chiller will vary during the day, being equal or lower to 0.70, due to the fluctuation of the outlet Temperature of the collector. This variation is not shown here but will be analysed in the next phase of this project.

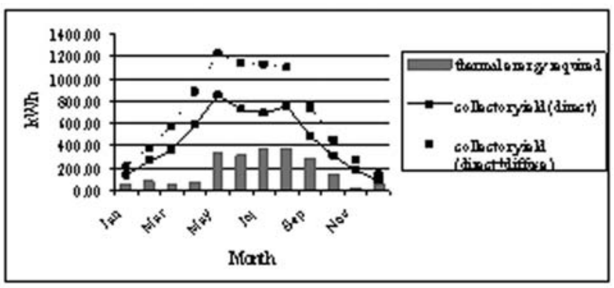

Figure 6. The requirement of thermal energy to cover the cooling demand for the reference model (9m^2 collector, 45^o tilt South) contrasted to the collector yield for a year. (Ecotect weather data used for both figures).

Nevertheless, at a daily level, the fluctuations of loads are far greater than the averages shown in Figure 6. Figure 7 shows that on the 20th of May (peak cooling) very early in the morning and between 19:00 and 23:00 there is insufficient incident solar energy to cover the cooling demand. It is also possible that the collector's yield with diffuse incident solar energy will be lower than the one estimated in Figure 7. This issue will be investigated during the STACS project later on.

If that is the case then insufficient levels of solar energy for the cooling requirement will be experienced also before 09:00. All this energy could potentially have been supplied from a TES component. Such a component could also bring an additional benefit to the system efficiencies, as it could maintain the temperature of the water at the inlet of the chiller at appropriate levels so that the maximum COP is achieved for the chiller.

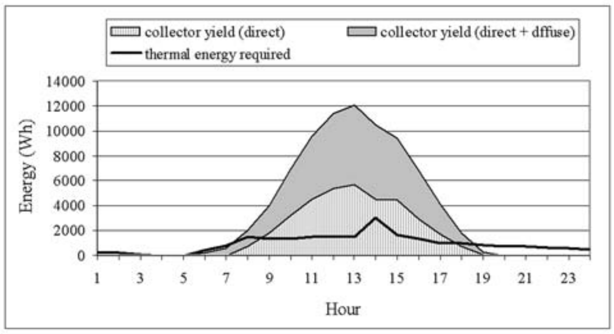

Figure 7. The daily requirement of thermal energy to cover the cooling demand for the reference model (9m^2 collector, 45^o tilt South) contrasted to the collector yield (Ecotect weather data used for both figures).

3.3 A preliminary study on the TES sizing

As discussed before, the peak cooling demand is recorded on the 20th of May, but the month with the highest total cooling load is August. To derive some initial conclusions about the size of the store, the hourly cooling requirement is calculated for the periods 7th May to 28th May and 6th Aug to 27th Aug.

A simplified ideal (no losses) model was created in Excel to size and analyse the behaviour of the store. Whenever the chiller demand for thermal energy is lower than the availability from the solar collectors, thermal energy is accumulated in the TES "tank". On the other hand, when the demand exceeds the availability, thermal energy is withdrawn from the store.

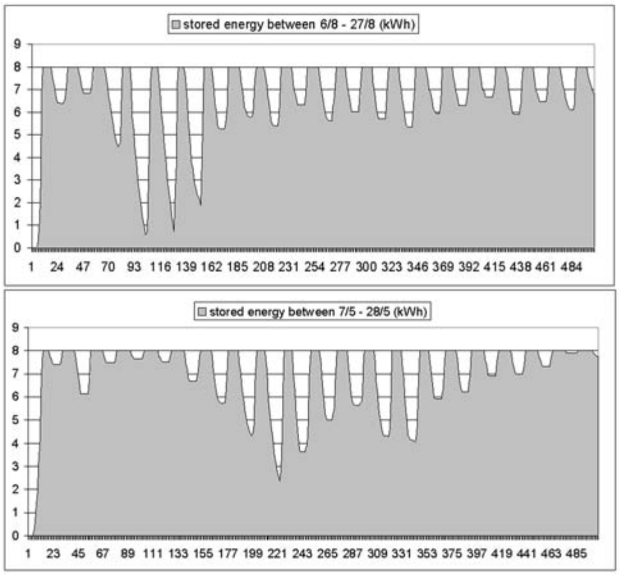

Figure 8 shows that if the store had been sized according to the day when the annual peak cooling requirement occurs (20th of May) this would have given a 6 kWh store which would Figure 8. Storage charging/discharging during two critical periods of the year (hourly data)

have been insufficient to cover the requirements during August.

3.4 Limitations of the model used

The admittance method, used to calculate the thermal model in the simulations described above, is a simplified calculation with well-known limitations (Rees et al, 2000). It is appreciated that there is a certain level of inaccuracy in the thermal model prediction described above, but the model provides relative accuracy, very useful for the prediction of general trends related to the various model's components.

Nevertheless as the project continues, other software validated for purpose will be used to model the systems' components (collectors, TES, distribution system). It was also found that hourly analysis in ECOTECT is very time consuming as hourly data is only provided on a 24-hour basis. It is also expected that simulations at a smaller timescale (5-min, 1-min intervals) might be required for better understanding of the systems. Therefore TRNSYS models will be created and the output of the TRNSYS multizone building (type 56) will be compared to the one from ECOTECT. This is of particular importance, as ECOTECT provides a user-friendly 3D interface, much more intuitive to architects and designers and it is among the interests of this work to identify the level of reliability of these preliminary results.

4. CONCLUSIONS

A thermal modelling analysis was undertaken on a case study representing a particular new build (2000) dwelling located in Cardiff, UK.

Using relatively realistic descriptions of the building's geometry and structure and the fluctuations in the internal gains (due to occupancy, appliances and lighting) the modelling shows an annual cooling demand of 1472 kWh with a peak of 2.1 kW. This shows that there is an emerging need for cooling to be provided on modern UK dwellings.

Preliminary analysis shows that a 9m^2 Solar Thermal collector would be sufficient to deliver enough energy to drive an absorption chiller to meet this demand, if a TES component was incorporated in the system. A first estimation of the required store gives a capacity of 8kWh if no losses are considered.

ACKNOWLEDGEMENTS

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