The IRG03 Formula Student car under construction in Racing Green's workshop

Fuel for thought

A team at Imperial College London is amassing experience in the design and construction of alternative-fuel race cars

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Imperial Racing Green is a flagship undergraduate teaching project in which students design, build and race zero-emission motorsport vehicles. In 2008 it involved 103 students and 33 academics from eight departments.

The project began in 2006 as a loose coalition of undergraduate and postgraduate students and a few staff at Imperial College in response to an invitation from Formula Zero – a company set up to popularize hydrogen fuel-cell technologies through motorsport – asking universities from around the world to compete in a new zero-emissions international race series involving hydrogen fuel cell-powered go-karts.

By the summer of 2007 the team had managed to secure seed funding from the EnVision project at Imperial College to build a prototype vehicle, IRG01, and pay some students to build the vehicle over the summer. The vehicle was powered by a 1.2kW Ballard Nexa fuel cell system combined with a large (48V, 800A, 1.5kWh) lithium polymer battery system provided by REAP systems and using Kokam cells. Permanent magnet Lemco LEM200 motors were used to power each rear wheel, and the bus voltage was kept to a maximum of 48V with a DC/DC converter regulating the fuel cell to operate in constant power mode – effectively a range extender.

Building a prototype was an immensely valuable experience and very useful when designing and building the Formula Zero competition vehicle, IRG02. This was particularly true considering the unknown aspects of much of the technology, and it enabled us to identify early what would be the most challenging aspects. The biggest problem was the DC/DC converter, as the device used on IRG01 was designed as a wall-mounted stationary device, which meant it was always unreliable. We knew looking for the right DC/DC converter for IRG02 should be top of the list.

The Radical SR8-based Racing Green Endurance (RGE) plug-in EV supercar is being built by a team of 10 students at Imperial

The main powertrain components for IRG02 consisted of a Hydrogenics HyPM 8.5kW fuel-cell power module (FCPM), a step-down DC/DC converter, two Maxwell 165F 48V supercapacitor banks, two motor controllers and two DC brushed motors. The kart can fundamentally be described as a fuel cell supercapacitor hybrid i.e. the supercapacitors act as a temporary energy storage medium for power from the fuel cell.

Hydrogen is stored on board the kart in a pressurized cylinder, and is transported through a hydrogen feed system to the fuel cell. The feed system contains a pressure regulator to step down the cylinder pressure to the required operating pressure of the fuel cell. In order to protect the FC from over-pressurization, three valves are in place after the regulator: a manual shut-off valve, which can be closed in the case of an emergency; a solenoid valve, which is activated by the control system; and a relief valve, which will purge the hydrogen in the case of over pressurization. There is also an additional manual valve in the system to purge the system of hydrogen when needed.

The fuel cell has its own balance of plant system (air filters, humidifiers, cooling system). The electricity produced in the fuel cell is passed through the step-down DC/DC converter, which converts the fuel-cell output voltage of 76V to the kart operating voltage of 48V. The DC/DC output is passed through LC filters to smooth the signal, and is then stored in the two parallel supercapacitor banks until the 48V limit of the capacitors is reached. As the supercapacitor voltage reaches 46V the fuel cell begins to ramp down until the voltage reaches 48V, after which it goes into standby mode. As the throttle pedal is pushed down, electricity flows from the supercapacitors to the electric motors via the motor controllers.

> "Power is transmitted to the rear wheels via a chain and sprocket arrangement. The rear axle is split, so independent control of the speed or torque of each rear wheel is possible"

Power is transmitted to the rear wheels via a chain and sprocket arrangement. The rear axle is split, which means that independent control of the speed or torque of each rear wheel is possible to optimize the vehicle dynamics. Currently a simple active steering program is used, which works by taking the steering angle and multiplying the power input to the outer motor by a gain proportional to the angle. As a result, the outer wheel will spin faster than the inner wheel, hence the kart can corner more quickly. Another advantage of using DC brushed motors is the ease with which regenerative braking can be implemented. Regenerative braking allows kinetic energy to be recovered by the motors while the kart is decelerating. This recovered kinetic energy is then stored in the supercapacitors ready for the next acceleration event.

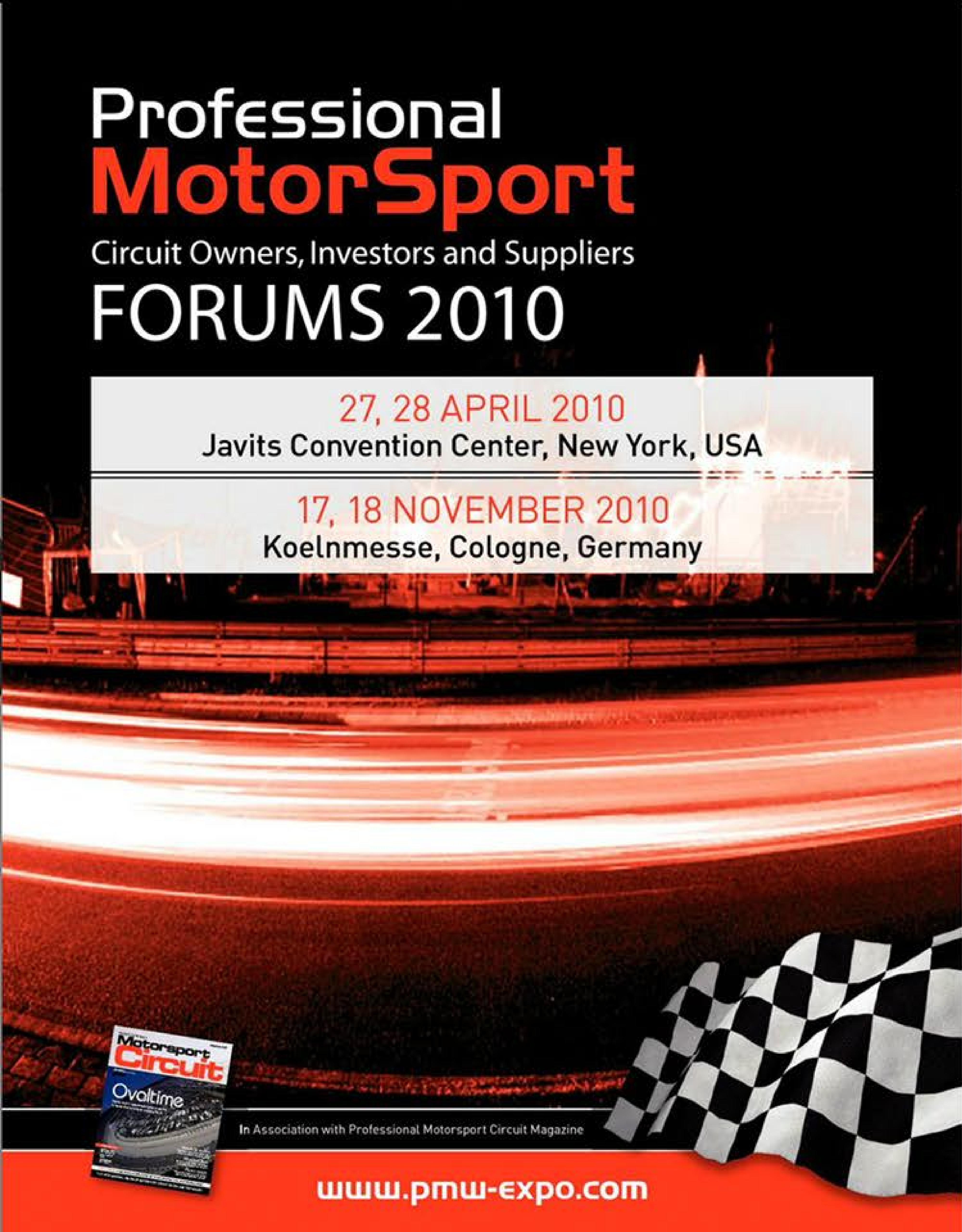
Having built a successful entrant for the Formula Zero competition in 2008 and 2009, Racing Green turned its attention to another challenge. The well-known Formula Student UK (FS) competition, which started life as the Formula SAE (FSAE) event in the USA and has since spread around the world, challenges universities to produce a small 'formula'-style race car to compete in various static and dynamic events. This has historically been a competition exclusively for ICE powered cars, but in 2008 a new alternative-fuels category – Class 1A – was introduced for the UK event. This built on the freedom in powertrain design permitted by the Formula Hybrid competition in the USA, itself a spin-off FSAE-based series inaugurated in 2007.

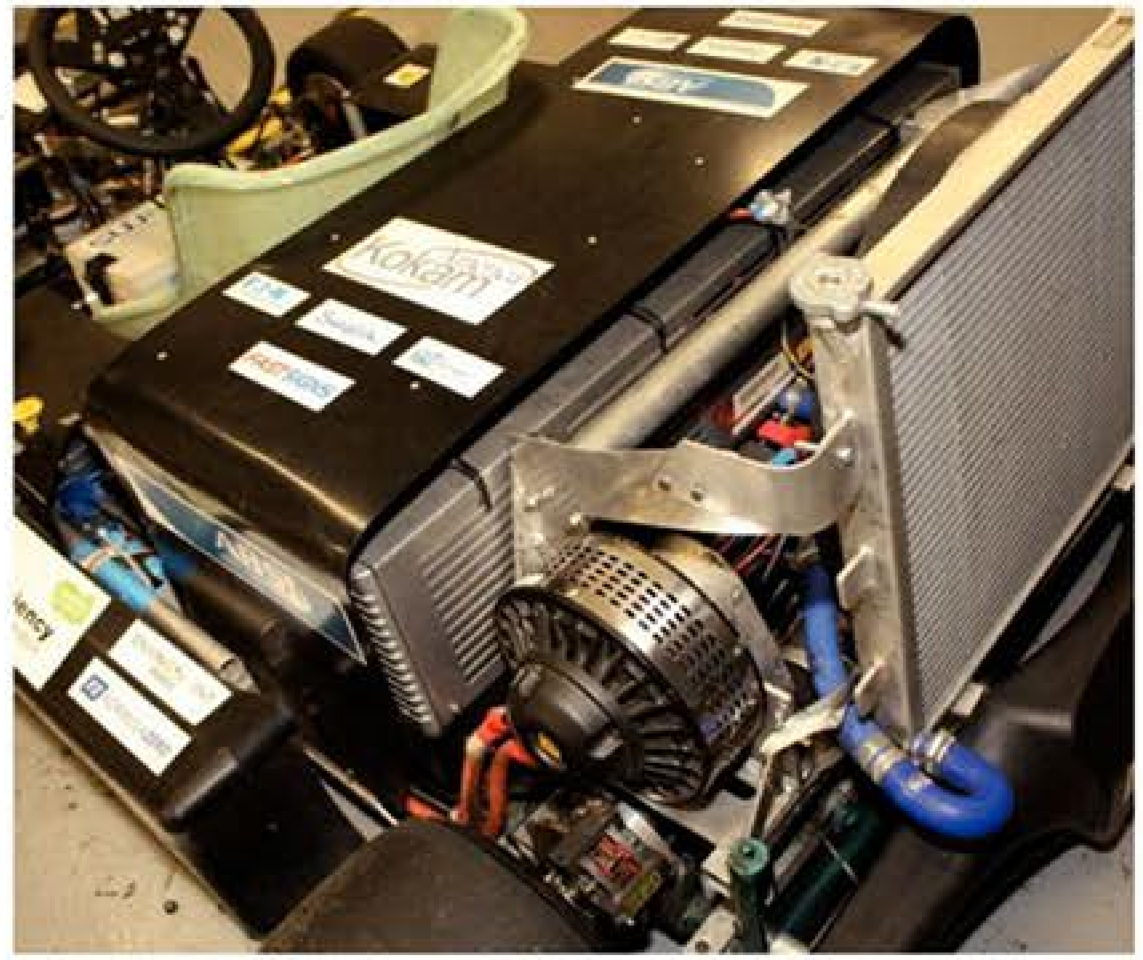
Starting in October 2007, Racing Green embarked on a two-year plan to create a vehicle to enter the competition as a design in 2008 and as a complete car in 2009. The design concept for the car, IRG03, was based around a battery-fuel cell hybrid powertrain system.

The final powertrain system involved the creation of a bespoke battery pack designed in-house with help from ABSL, consisting of 432 Kokam lithium-polymer cells providing 7.5kWh at a voltage of c.300V in a custom support structure. Battery management is provided by REAP Systems modular BMS that monitors individual cells and communicates with the vehicle control system via CAN. In series with the pack, and acting as a range extender, is a 4kW air-cooled Pearl hydrogen fuel cell, which is stepped up from c.75V to the battery voltage via a DC/DC converter. Power from the battery is supplied via analog motor controllers to a Perm 120W 11kW permanent magnet synchronous motor for each wheel. The team incorporated the mounting of the motors via water-cooled plates, which form a structural part of the chassis.

All the vehicle systems are controlled through a National Instruments CompactRio PAC, programmed through the use of LabVIEW software. The control system allows individual control of the motors either through open-loop current control mode, or in closed-loop velocity control mode, taking throttle pedal position and steering position as the driver input, thereby enabling the use of an electronic differential.

Drive to each of the four wheels is transmitted via a motor face-mounted





IRG02 Formula Zero (left); and the first-generation fuel cell system for IRG05 (below)

Neugart epicyclic reduction gearbox, through conventional CV joints and half shafts to the hubs. Taking advantage of the motor position, inboard mechanical brakes are mounted directly on the motor shaft, reducing unsprung mass and reducing the braking torque required. The other mechanical systems are conventional, including unequal-length carbon-fiber wishbones, with suspension provided via coil-over dampers activated through a pushrod and rocker arrangement all round.

Ultimately the complexity of the vehicle was its downfall, with time running out to prove the vehicle adequately before the race. Although there was the disappointment of being unable to compete in the dynamic events of the 2009 FS UK competition, the team was rewarded with the award for the 'most innovative/effective design'.

The team has also worked hard over the summer to get the car running as a testbed for future development, and a number of very important of lessons from the IRG03 exercise have been learned. A battery-heavy hybrid with FC range extender is not the best solution for a track vehicle. The small range required in the 30-minute endurance event of the competition does not merit the extra complexity that the fuel cell brings, despite having a system volumetric energy density (including FC, hydrogen cylinders and control system) of about 20% that of the battery pack, and a gravimetric energy density of about 50%. This configuration is suitable for a road vehicle, but there are two better solutions for a track car: either fully electric, or a fuel cell supercapacitor hybrid.

The former will be used for IRG03's successor, IRG04, which will enter Formula Student in 2010/11. IRG04 will use a reconfigured IRG03 battery pack to integrate further safety control systems, and will act as the sole power source on the car. The vehicle concept emphasizes simplicity, and will strive to minimize the number and complexity of the car's systems in order to focus on producing a reliable vehicle that concentrates on maximizing performance as a race car. It will also produce a good mechanical base from which to evolve future vehicles and return to the proven fuel cell supercapacitor hybrid powertrain configuration used in IRG02. This allows the fuel cell to run at its optimum efficiency point continuously, while the supercapacitors allow the rapid power delivery to provide the rapid acceleration required for racing, and robust acceptance of regenerative braking energy.

IRG05, with a further developed powertrain, will be the fifth vehicle to be produced by the Imperial Racing Green project. It will feature two 8kW fuel cell stacks provided by Johnson Matthey and Nedstack, which will be hybridized with a large supercapacitor bank. The balance of plant (BoP) for the fuel-cell system is currently being designed and built by the undergraduate students, and is broken down into three main areas: the air systems, hydrogen systems and cooling systems. The completed system will provide roughly 12kW of net power. Over the last academic year a team of nine students designed and built the first-generation prototype 'in-house' fuel-cell system in eight months, and tested it successfully with an end-of-life stack.

The current air system features an Eaton M24 Roots-type turbocharger, which is powered by a 48V LEM-200-127 Lynch electric DC motor capable of up to 11kW. This is controlled with the use of a 4QD 300 motor controller for an operating speed of approximately 7,000rpm. The complex inlet manifold for the compressor was designed in the university and then outsourced to be laser sintered.

For the air side humidification, a Perma Pure FC-400-10 unit was used. This recycles the humid cathode exhaust gas at an operating temperature of around 65°C.

The hydrogen system has been designed with a recirculation loop to improve hydrogen fuel economy with a Thomas diaphragm pump. A custom-made water separator unit has also been designed and manufactured with the dual purpose of heat exchange and anode side humidification. After FEA validation, this was constructed from polycarbonate and plastic, welded in order to ensure the unit could handle the operating pressures. A solenoid value controlled by a duty cycle PWM provides a means to purge inert gases that cross over the cell membranes from the cathode side of the stack, to improve cell performance.

The cooling system uses a 24V DC Ametek fan mounted on a Honda Civic V radiator with a Jabsco centrifugal high-pressure cyclone pump. The pump is controlled with a SyRen 25A regenerative motor controller on a deionized water loop to maintain an operating temperature of approximately 65°C.

The control of the BoP components is achieved with a CompactRio (cRio) control unit using a LabVIEW-based program.

The full fuel-cell system has so far been successfully tested up to 3kW. Early problems were encountered with the startup of the stack and getting the coolant fluid up to the operating temperature. Future development work includes replacing the compressor with a low-pressure air blower to reduce parasitic losses, reducing the weight of the rest of the system so as to make it more race focused, and looking at whether a heat pump could be used for FC cooling, and the optimization of end plates.

In a spin-off project from Racing Green, a team of 10 students have volunteered to design, build and race a plug-in EV supercar capable of navigating the Pan-American Highway. From the most southerly city on the planet, Ushuaia in Argentina, all the way to Prudhoe Bay on Alaska's northern coast, Racing Green Endurance will be traveling the world's longest road, aiming to challenge the public perception of EVs as slow, unattractive and of limited range.

Radical Sportscars is sponsoring the project by providing a Radical SR8. This is an impressive foundation for the team to design a new electric powertrain optimized to minimize losses and maximize endurance.

EVO Electric has sponsored two of its AF140 motors that will be custom-wound to operate within their optimum efficiency band at cruising speed, thus eliminating the need for a gearbox and giving the car a top speed of 124mph. With 650Nm and 70kW from each motor, and despite the car being optimized for long-range cruising, it can still achieve an impressive 0-60mph acceleration time of 6.5s. If the car was set up for racing, however, that could be reduced to under 4s.


IRG03 race car at Formula Student, summer 2009

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In order to control the motors and achieve the most from using two motors on a split rear axle, the car will incorporate two motor drives from Rinehart Motion Systems. These compact drives can handle up to 100kW each, giving us plenty of power to achieve our top speed and acceleration. The drives will communicate with the central control unit – a National Instruments CompactRio – and this will keep the car stable under wet road conditions by using a torque control electronic differential. The drives will also receive messages from the CANbus in the car, and will reduce power under high-temperature conditions to protect the vehicle from misuse. In addition, the CompactRio can monitor the safety circuits in the car in order to disable motor use in an emergency.

The car runs on a modular pack built from Thunder Sky's lithium-iron phosphate cells. With each cell delivering 100Ah of capacity, and with 169 cells on the vehicle, the battery pack stores an impressive 55.8kWh of energy – even more than that of the current world leader, the Tesla. With all the cells in the pack strung in series to minimize I2R losses and to match the motor voltages, the car requires a battery management system (BMS) in order to keep all the cells balanced and safe.

RGE has teamed up with Frazer-Nash to build a customized BMS for the car. It will also monitor theoretical range, pre-charge circuits, safety contactors, temperature and state of charge of the whole pack while communicating with the rest of the vehicle in order to optimize energy use for the various environments and drive cycles the car will undergo.

Losses are further minimized by removing the need for a mechanical diff; two motors on a split rear axle are used instead. On a US FTP Highway drive cycle the vehicle should achieve 13kWh/100km from battery to wheel, giving it a range of nearly 248 miles.