POWER TRANSFORMER CORE OPTIMIZATION ENABLES DRAMATICALLY INCREASED POWER DENSITY

Introduction

In power electronics maximizing density and efficiency is critical but power magnetics are often limited by the existing core shapes and sizes. In the past the ability to design custom core and bobbin platforms was severely limited do to three factors. First, the optimization process was slow relying on cumbersome 2D design process using IEC60205 standards to calculate parameters. Second, historically core tooling costs were excessively high (>$18K) and third lead times were long (>18wks). These limitations have now been minimized with costs <$5K, lead-times <4wks and modern finite element analysis tools allowing for accurate and fast 3D design. Optimizing a core allows the magnetics designer to ensure that the flux utilization is balanced and provides another variable in the design process.

In any transformer design (or coupled inductor flyback design) one is using a basic equation to 'select' the appropriate core and turns for a given application.

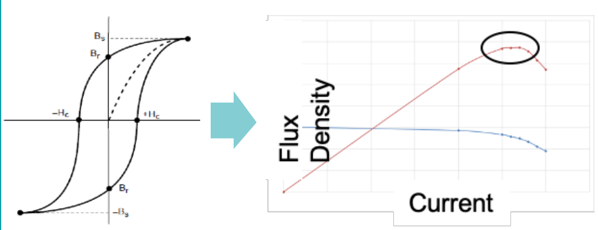
Inductor: Nmin = Bmax * Ae / (L * Ipk)
Transformer: Nmin = Bmax * Ae / (Vp * dt)

N = number of primary turns, B = flux density, A=core area, L=primary inductance, I=primary current, V=primary voltage, dt=time

One is always looking to run a magnetic design at some maximum flux density (either limited by saturation or limited thermally due to core loss) and as such assuming the appropriate core material has been selected, Bmax is fixed for any given application.

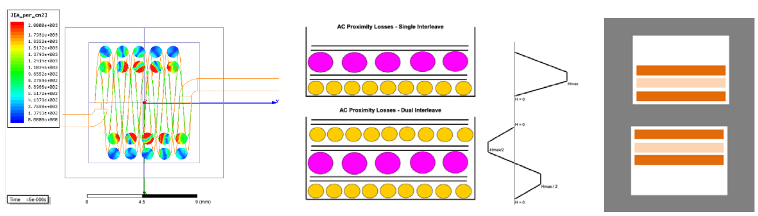
The application sets the requirements for L & Ipk or Vp & dt so this leaves the turns (Nmin) and core area (Ae) as the only true variables. The ability to design and use an optimized core means the Ae can be maximized for a given package size which means turns, and therefore copper losses, minimized. As an example we will compare an industry standard EP platform against an optimized EP+ version.

Saturation (B_{max})



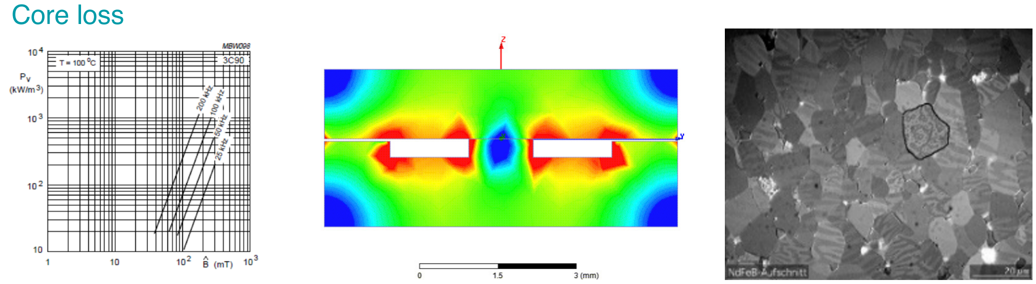
B_{sat} 4200-5300G B_{max} 2700-3200G

AC proximity losses



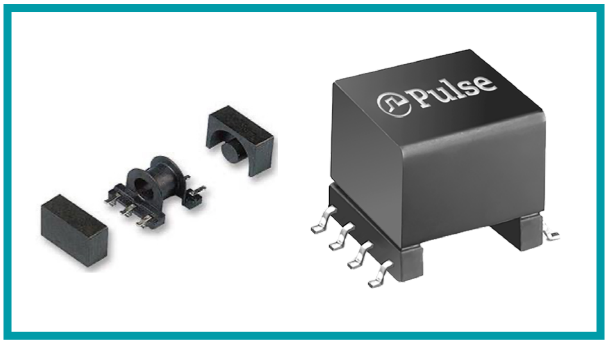
Minimizing AC Proximity losses necessitates keeping winding builds low but this leads to poor window utilization when using standard cores.

Core loss



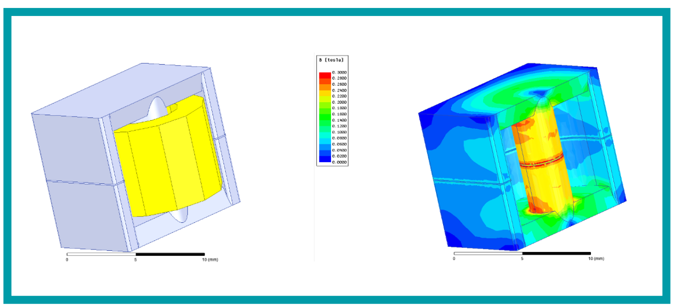
Minimizing AC Proximity losses necessitates keeping winding builds low but this leads to poor window utilization when using standard cores.

Design Example – Industry standard EP7 Core Platform



The EP core platform has become a defacto industry standard for DC/DC power applications due to its relatively compact size, inherent self-shielding and suitability for PoE (15W) and PoE+ (30W) applications such as VoIP phones, security cameras and infotainment devices. As power demands of these devices has increased to include PoE++ (60W) and high-power PoE (100W) and board real estate has become more precious it is increasing difficult to design a suitable transformer using industry standard cores.   In order to meet customer expectations that existing footprints cannot grow but through-power must increase it is necessary to review the industry standard cores and develop optimized alternatives.

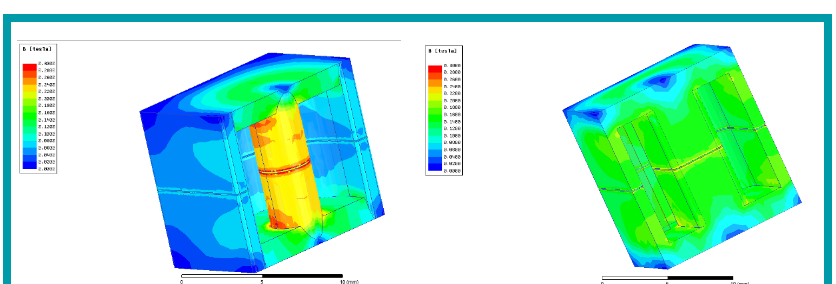
Finite Element Analysis modelling of the industry standard EP7 core is shown below.   Core is modelled using a single turn winding to induce flux (left view) and then the flux distribution is examined (right view).



EP7 Reference Information

Effective Core Area: 0.107cm2
Effective Core Volume: 0.165cm3
Overall SMT Platform Dimensions: 13.3mm x 10.7mm x 9.3mm
Overall SMT Platform Volume: 1.32cm3

In a well designed core the magnetic flux density should be as even as possible (same coloring) throughout the core. It is clear from the above image that the flux density is much higher (3x) on the center leg (yellow) than the outer legs of the core (blue) which leads to sub-optimum magnetic component designs. As indicated, the true variables for the initial transformer design are the effective core area (Ae) and turns (N) and one is always trying to optimize the effective core area within an allotted volume (ie: maximize power density). The goal is to improve the design but maintain the exact same industry standard footprint. Using FEA it is possible to quickly manipulate the industry standard core structure (in 2D or 3D) to create a uniform flux distribution and a higher effective core area.



Standard EP7 **Optimized EP7+**

EP7+ Reference Information

Effective Core Area: 0.256cm2
Effective Core Volume: 0.602cm3
Overall SMT Platform Dimensions: 13.3mm x 10.7mm x 15mm
Overall SMT Platform Volume: 2.13cm3

The EP7+ has a Ae of 0.256cm2 which is an increase of 2.4x the standard EP7 which enables a 2.4x reduction in primary turns. Although one might think that having less turns around a larger circumference core may result in similar conductor losses this is not the case. Assuming the same wire diameter, the DCR/turn increases with the circumference (PI*d) of the center leg but the number of turns decreases with the center post area (0.25*π*d2). As a result, a larger center post (with uniform cross section throughout the remaining core) will always result in lower conduction losses (assuming of course that proper attention is paid to AC proximity affects when designing the windings). It should be noted that for this particular design example the overall platform height was increased from 9.3mm to 15.0mm (61%) as it was desired to utilize all available height in the end-applications. This additional height does help in the optimization but as will be shown the major impact is due to the uniform flux distribution.

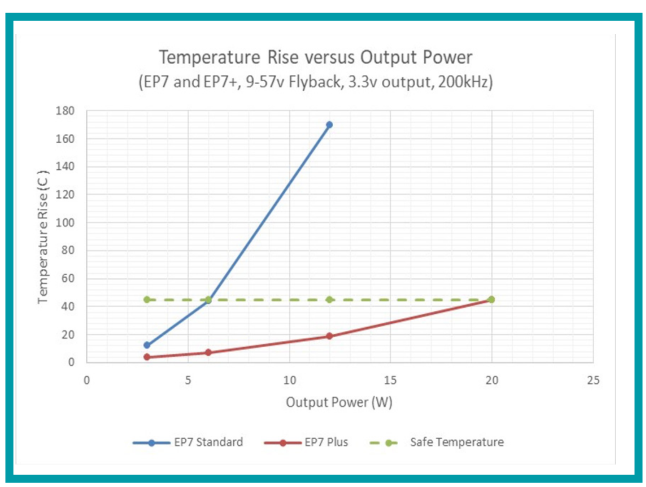
Transformer Design Comparison: EP7 and EP7+, Active Clamp Forward

Pulse Electronics has developed three optimized platforms (EP7+, EP10+ and EP13+) but for illustration purposes we will continue with the EP7/EP7+ comparison. To illustrate the improvement Pulse designed a series of transformers at four different output powers for a continuous mode flyback topology using a standard PoE input (9-57v), typical frequency (200kHz) and 3.3v output.

Application: CM Flyback, 200kHz, 9-57v input, 3.3v output				
	3W	6W	12W	20W
Turns Ratio	5 to 1			
Primary L (uh)	56.5	28	14.1	10
Ipk_pri (A)	0.89	1.78	3.56	5.4
Irms_pri (A)	0.5	1	2	3.3
Irms_sec (A)	1.77	3.54	7	10.65
EP7 Standard Design – 13.2mm x 11.5mm x 9.3mm				
Power Loss	93mW	315mW	1195mW	3100mW
Temperature Rise	12C	44C	170C	437C
EP7+ Optimized Design – 13.2mm x 11.5mm x 15.0mm				
Power Loss	64mW	100mW	242mW	535mW
Temperature Rise	4C	7C	19C	45C

When used in a flyback transformer application the EP7+ can do 20W of through-power 2x the power density of the standard EP7

There are many ways to compare transformer performance by either looking at power loss or temperature rise. A typical 'safe' temperature rise is 45C above ambient. Using this as the base line it shows that the EP7 can only handle 6W of throughput power whereas the EP7+ can handle 20W (3.3x). As noted earlier the EP7+ does use up additional height but this change can be normalized by looking at power density. The standard EP7 is 6W/1.32cm3 or 4.5W/cm3, the EP7+ is 20W/2.13cm3 or 9.4W/cm3 which means power density has improved by a factor of 2.

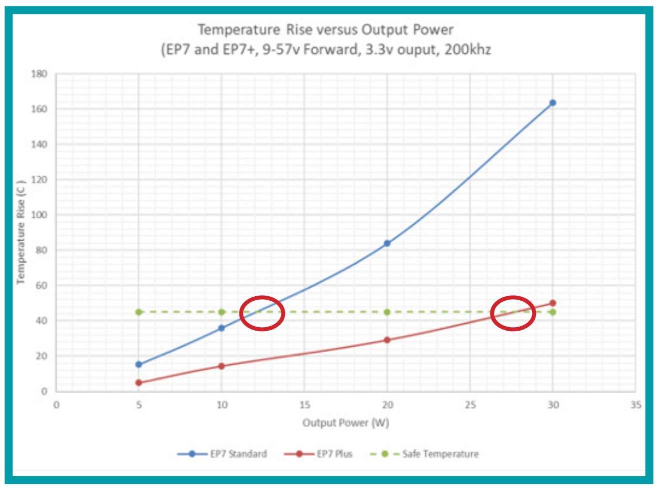


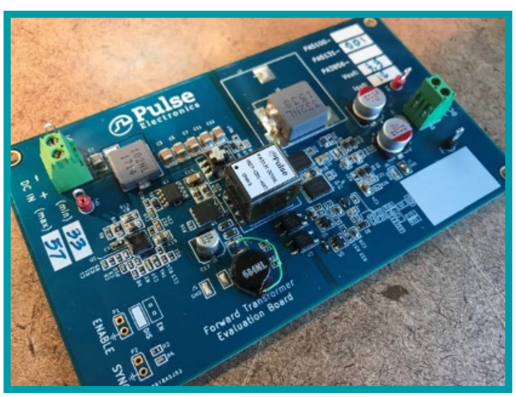
Pulse Electronics has developed three optimized platforms (EP7+, EP10+ and EP13+) but for illustration purposes we will continue with the EP7/EP7+ comparison. To illustrate the improvement Pulse designed a series of transformers at four different output powers for an active clamp forward topology using a standard PoE input (9-57v), typical frequency (200kHz) and 3.3v output.

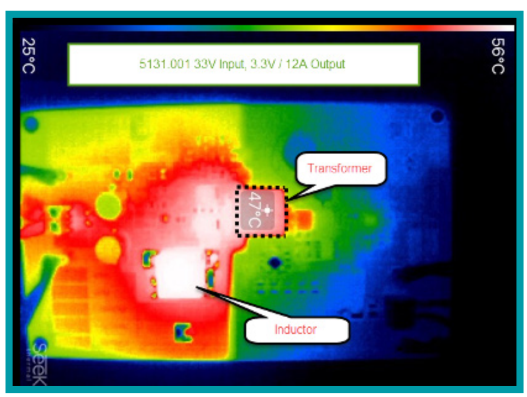
Application: CM Flyback, 200kHz, 9-57v input, 3.3v output				
	5W	10W	20W	30W
Turns Ratio	1.5 to 1			
Irms_pri (A)	0.83	1.66	3.33	4.99
Irms_sec (A)	1.12	2.25	4.49	6.74
EP7 Standard Design – 13.2mm x 11.5mm x 9.3mm				
Power Loss	29.8	17.2	17.2	17.2
Sec DCR (mOhms)	31	3.2	3.2	3.2
Power Loss	90mW	230mW	470mW	1070mW
Temperature Rise	15C	36C	29C	50C
EP7+ Optimized Design – 13.2mm x 11.5mm x 15.0mm				
Power Loss	90mW	230mW	470mW	1070mW
Temperature Rise	5C	14C	29C	50C

When used in a flyback transformer application the EP7+ can do 20W of through-power 2x the power density of the standard EP7

Using the same 45C temperature rise metric as previous the above shows that the EP7 can only handle 12W of throughput power whereas the EP7+ can handle 28W (2.3x). As noted earlier the EP7+ does use up additional height but this change can be normalized by looking at power density. The standard EP7 is 12W/1.32cm3 or 9.0W/cm3, the EP7+ is 28W/2.13cm3 or 13W/cm3 which means power density has improved by a factor of 1.5x.





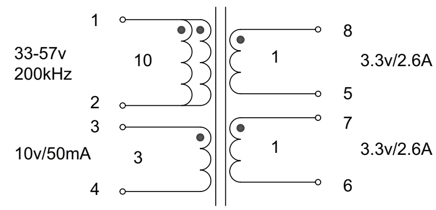
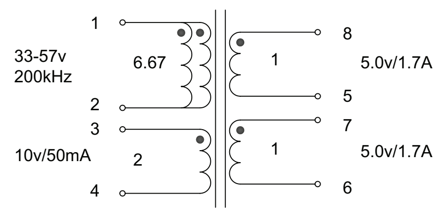
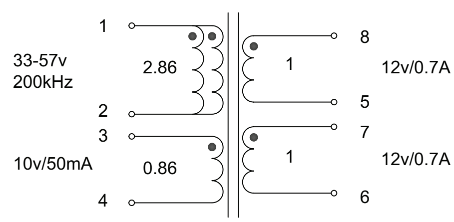
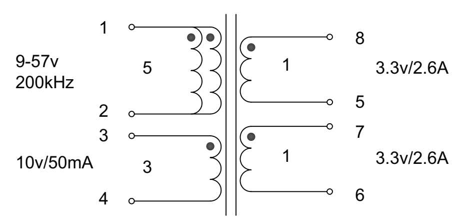


Simulation, calculation and design support the advantage of the FEA optimized core solution but in order to prove out the advantage Pulse designed a flyback and forward converter demo board. Circuit efficiency and thermal measurements were completed for a wide-range of input voltages and output power levels on both EP7/EP7+ and EP10/EP10+ designs. A sub-section of the data is shown below.

Date	Xformer	Topology	Vout	Iout	Vin	Iin	Pin	Pout	Efficiency	Xformer Temp	PCB Temp	Xformer Rise	Lout	
Forward														
19-Jul	5100.001	Fwd	3.32 V	12.0 A	33.0 V	1.32 A	43.66 W	39.84 W	91.3%	58.6 °C	33.0 °C	25.6 °C	3.3uH	Synch Re
19-Jul	5100.001	Fwd	3.32 V	12.0 A	57.0 V	0.77 A	44.06 W	39.84 W	90.4%	55.6 °C	32.2 °C	23.4 °C	3.3uH	Synch Re
19-Jul	5100.001	Fwd	3.32 V	9.0 A	33.0 V	0.98 A	32.27 W	29.88 W	92.6%	50.2 °C	31.4 °C	18.8 °C	3.3uH	Synch Re
19-Jul	5100.001	Fwd	3.32 V	9.0 A	57.0 V	0.57 A	32.66 W	29.88 W	91.5%	51.8 °C	33.4 °C	18.4 °C	3.3uH	Synch Re
19-Jul	5131.001	Fwd	3.32 V	12.0 A	33.0 V	1.30 A	42.97 W	39.84 W	92.7%	52.2 °C	32.0 °C	20.2 °C	3.3uH	Synch Re
19-Jul	5131.001	Fwd	3.32 V	12.0 A	57.0 V	0.76 A	43.26 W	39.84 W	92.1%	54.6 °C	34.6 °C	20.0 °C	3.3uH	Synch Re
20-Jul	5131.004	Fwd	3.31 V	12.0 A	9.0 V	5.24 A	47.16 W	39.72 W	84.2%	72.4 °C	49.6 °C	22.8 °C	5.6uH	Synch Re
20-Jul	5131.004	Fwd	3.31 V	12.0 A	24.0 V	1.93 A	46.20 W	39.72 W	86.0%	73.8 °C	49.2 °C	24.6 °C	5.6uH	Synch Re
20-Jul	5131.004	Fwd	3.31 V	12.0 A	36.0 V	1.27 A	45.58 W	39.72 W	87.2%	75.8 °C	48.8 °C	27.0 °C	5.6uH	Synch Re
20-Jul	5131.004	Fwd	3.31 V	12.0 A	56.0 V	0.78 A	43.79 W	39.72 W	90.7%	80.6 °C	48.2 °C	32.4 °C	5.6uH	Synch Re
20-Jul	5100.004	Fwd	3.31 V	9.0 A	9.0 V	3.84 A	34.56 W	29.79 W	86.2%	70.8 °C	47.8 °C	23.0 °C	5.6uH	Rect
20-Jul	5100.004	Fwd	3.31 V	9.0 A	24.0 V	1.45 A	34.68 W	29.79 W	85.9%	73.8 °C	49.6 °C	24.2 °C	5.6uH	Rect
20-Jul	5100.004	Fwd	3.31 V	9.0 A	36.0 V	0.96 A	34.63 W	29.79 W	86.0%	78.6 °C	51.4 °C	27.2 °C	5.6uH	Rect
20-Jul	5100.004	Fwd	3.31 V	9.0 A	57.0 V	0.58 A	32.83 W	29.79 W	90.7%	91.4 °C	54.2 °C	37.2 °C	5.6uH	Rect
Flyback														
20-Jul	5130.001	Fly	3.32 V	9.0 A	33.0 V	1.09 A	35.97 W	29.88 W	83.1%	63.8 °C	40.8 °C	23.0 °C		Rect
20-Jul	5130.001	Fly	3.32 V	9.0 A	57.0 V	0.62 A	35.45 W	29.88 W	84.3%	65.4 °C	41.8 °C	23.6 °C		Rect
3-Sep	5305BNL	Fwd	3.30 V	3.0 A	9.0 V	1.31 A	11.79 W	9.90 W	84.0%	50.0 °C	33.0 °C	17.0 °C	5.6uH	Rect
3-Sep	5305BNL	Fwd	3.30 V	3.0 A	33.0 V	0.40 A	13.20 W	9.90 W	75.0%	46.0 °C	32.0 °C	14.0 °C	5.6uH	Rect
3-Sep	5305BNL	Fwd	3.30 V	3.0 A	56.0 V	0.25 A	14.00 W	9.90 W	70.7%	55.0 °C	33.0 °C	22.0 °C	5.6uH	Rect
3-Sep	5305BNL	Fwd	3.30 V	6.0 A	9.0 V	2.60 A	23.40 W	19.80 W	84.6%	59.0 °C	33.0 °C	26.0 °C	5.6uH	Rect
3-Sep	5305BNL	Fwd	3.30 V	6.0 A	33.0 V	0.74 A	24.42 W	19.80 W	81.1%	62.0 °C	33.0 °C	29.0 °C	5.6uH	Rect
3-Sep	5305BNL	Fwd	3.30 V	6.0 A	56.0 V	0.44 A	24.64 W	19.80 W	80.4%	62.0 °C	33.0 °C	29.0 °C	5.6uH	Rect

An analysis of the data verified the superior performance of the optimized core and is in line with the calculated values (1.8x measured improvement for flyback compared with 2.0 calculated and 1.3x measured improvement for forward compared with 1.5x calculated). A relatively simple optimization of a core platform using FEA results in a 30% to 80% improvement in transformer power density (W/cm3). The relatively low tooling costs and short lead-times of customized approaches makes this a very effective means of improving power supply design. Finite Element Analysis has been shown through core simulation, transformer calculation and in-circuit testing to be an effective design choice for optimizing transformer power density.

- *Industry standard footprint, 2X more power handling*
- ***Power Range:*** *PA5099.XXXNL up to 17W; PA5100.XXXNL up to 27W*
- ***Height:*** *15.5mm Max*
- ***Footprint:*** *13.6mm x 11.0mm Max*
- ***Topology:*** *Forward and Flyback*

Pulse PN	Electrical Specifications @25°C – Operating Temperature -40°C to 125°C [1]				Schematic
PA5099.001NL	Pri. Inductance	(1-2)	80	uH ± 10%	 Flyback Transformer
	Lk. Inductance	(1-2) w/ (5,6,7,8) shorted	1.0	uH Max	
	DCR	(1-2)	180	mΩ Max	
		(3-4)	130		
		(8-5)	12		
		(7-6)	12		
	Hi-Pot	Pri-Sec	2250	Vdc	
	K1 Factor		1563		
PA5099.002NL	Pri. Inductance	(1-2)	80	uH ± 10%	 Flyback Transformer
	Lk. Inductance	(1-2) w/ (5,6,7,8) shorted	1.0	uH Max	
	DCR	(1-2)	180	mΩ Max	
		(3-4)	130		
		(8-5)	24		
		(7-6)	24		
	Hi-Pot	Pri-Sec	2250	Vdc	
	K1 Factor		1563		
PA5131.004NL	**Pri. Inductance**	**(1-2)**	**13**	**uH Min**	 **Forward Transformer**
	Lk. Inductance	**(1-2) w/ (5,6,7,8) shorted**	**0.1**	**uH Max**	
	DCR	**(1-2)**	**7**	**mΩ Max**	
		(3-4)	**420**		
		(8-5)	**4**		
		(7-6)	**4**		
	Hi-Pot	**Pri-Sec**	**2250**	**Vdc**	
	K1 Factor		**1146**		
PA5131.005NL	**Pri. Inductance**	**(1-2)**	**13**	**uH Min**	 **Forward Transformer**
	Lk. Inductance	**(1-2) w/ (5,6,7,8) shorted**	**0.1**	**uH Max**	
	DCR	**(1-2)**	**7**	**mΩ Max**	
		(3-4)	**420**		
		(8-5)	**8**		
		(7-6)	**8**		
	Hi-Pot	**Pri-Sec**	**2250**	**Vdc**	
	K1 Factor		**1146**		

Written By: John Gallagher