Van de Graaff generator hazards

We have had another look at the safety of the Van de Graaff (VDG) generator in light of new information in electrical standards and from measurements of dome voltage.

Our original risk assessment on the Van de Graaff generator [1] was done theoretically. Using $C = 4\pi\varepsilon_0 a$ to get the dome's capacitance and taking the maximum voltage on the dome to be $3a$ MV, where a is the dome radius, the maximum value for the stored electrical energy was derived from $E = \frac{1}{2}CV^2$. Using the standard extant at the time [2], 1000 mJ of energy from a spark discharge was the limit set by us, it being the threshold at which everybody is affected severely from a spark. By calculation, a dome diameter of 25 cm can store, theoretically, 1000 mJ of energy. Therefore that became our limiting size. Any machine with a dome diameter bigger than 25 cm was declared dangerous.

There were several problems with this. Firstly it was based entirely on theory. Although it was probable that no machine would live up to scratch, we had no means of assessing by how much below par it would be. Secondly, there was concern that the limiting energy (1000 mJ) might be too big in that, in the words of the standard, it 'affects everybody severely'. Might not this limit be dangerously high? Thirdly, there is the knowledge that electrostatics is capricious. But what does that mean? Is it 'sometimes dud', in which case it fails to safety? Or is it 'sometimes unexpectedly lively', implying that it can overstep the mark?

With new VDGs appearing on the market, there was a need to assess them, adding pressure to revise our safety guidance. A complaint about one of these newcomers, the Edulab, had to be responded to. The complainant had written to say, "several members of staff have used it and felt quite uncomfortable – the 'shock' received has been quite unpleasant". With a diameter of 21 cm, well below our limit, might this be a VDG whose capriciousness was overstepping the mark?

Also a caution in an electrostatics' standard [3] issued after we had published our VDG guidance in 2002 had to be reckoned with. This said that discharges above 350 mJ "are considered to be a direct hazard to health".

The new approach we have taken has been to measure the voltage on the dome of a charged VDG by finding how far it will spark. There is a rule of thumb that the insulation of air breaks down at a potential gradient of 3 MV m^{-1}. From this, if the length of the longest spark gap were 10 cm, then the voltage would be 300 kV. This rule is refined in a new standard [4].

Figure 1 - Voltage measurement by means of standard air gaps. The dome on the right is being charged up. The dome on the left is connected to earth.

It has tables for voltage against length of spark gap for two adjacent conducting spheres, one charged, the other earthed, for different diameters[1]. Tabulated values range from between 10% to 25% lower than predicted by the rule of thumb at 3 MV m^{-1}.

We applied this method by setting up two VDGs side by side with their domes at the same height (Fig. 1). The dome of one machine was earthed. The other (the one under test) was allowed to charge up until sparking began. By repeating this procedure for lots of distances, we arrived at a value for the longest spark.

Four different VDG models were tested (Table 1). By comparing the ratios of the measured to theoretical voltages, a gauge of merit was found. The worst performance was 0.36; the best, 0.79. Indeed we reckoned that the best you would ever get from a VDG is 0.8 – resolving our fears on what to do about the capricious nature of electrostatics. 0.8 is as good or as bad as it gets, depending on how you look at it. We thereby derived hypothetical values for any machine at 2.4a MV, being the highest voltage that anyone could possibly reach from 'souping up' their machine.

Finding that all four of the VDGs can exceed 350 mJ hypothetically and that two of them do so in practice, the new safety limit we decided upon is 500 mJ (a compromise between 350 and 1000 mJ). Any machine discharging more than 500 mJ, or holding more that 5 μC of charge, would seem to be unsuitably hazardous.

In conclusion, any new type of VDG with a dome diameter exceeding 20 cm should be risk assessed by SSERC to find out whether it is safe for use.

[1] Strictly, the method applies best to ac voltage measurement. If used for dc, the uncertainties are not knowable.

Charging a person

We also reconsidered the risk of harm when a person – usually a pupil – is deliberately charged up and then discharged. During the time a machine is running the highest potential on the person making contact with the dome is limited to about 50 kV [2] by electrical leaking and sparking. The capacitance of the human body lies between 100 and 300 pF. Taking the top of this range (300 pF) to investigate the worst case, the energy to be discharged from the person would be 375 mJ and the charge stored on the person, 15 μC. A sudden discharge of this amount of energy and charge would certainly be disagreeable. It might be painful, but is unlikely to have any other direct effect.

The VDG does not charge up to its normal operating voltage when a person is touching the dome because the rate of leakage of charge from the person is too great. We tested this by charging up the author of this report and bringing up a second, earthed dome towards the charged one until there was a discharge across the air gap (Fig. 2). The voltage on the dome had about halved (Table 2).

Figure 2 - Determining the voltage on a dome when charging a person.

When several pupils link hands to form a chain from the person in contact with the dome, the capacitance of the system will become quite large. Nevertheless because of leakage and internal impedances [5] the voltage successive members of the chain reach will presumably fall from person to person. Therefore the system

Van de Graaff	Arco	EduLab	Frederiksen	Altay
Dome diameter (m)	0.215	0.210	0.220	0.278
Capacitance (pF)	12.0	11.7	12.2	15.5
Charge polarity	Negative	Positive	Negative	Positive
Spark gap (m)	0.042	0.075	0.120	0.104
Maximum voltage (by theory from dome diameter and 3 MV m^{-1} voltage breakdown) (kV)	323	315	330	417
Maximum voltage (by length of spark gap and 3 MV m^{-1} voltage breakdown) (kV)	126	225	360	312
Maximum voltage (by length of spark gap and reading off Table 2 in BS EN 60052:2002)	116	188	261	256
Ratio of voltages: Measured versus theoretical	0.36	0.60	0.79	0.61
Estimate from theoretical voltage				
Charge (µC)	3.9	3.7	4.0	6.5
Energy (mJ)	620	580	670	1,340
Derivation from actual voltage				
Charge (µC)	1.4	2.2	3.2	4.0
Energy (mJ)	80	210	420	510
Physiological effects	Slight discomfort	Disagreeable shock	Disagreeable or painful shock	Painful shock and risk of harm

Table 1 - Derivation of dome voltage by 3 methods.
Values of charge and energy as derived: (a) by a theoretical consideration of the dome diameter, and (b) from the BS EN air gap method.

is hardly likely to become dangerous unless everyone is well insulated from the floor by standing on plastic platforms. The fact that teachers have been doing this demonstration for years without harming anyone, so far as we are aware, bears this out.

Further details

The full report on VDG safety can be found on our website. It has test results on four different models of VDG, explaining how this comparative study helped establish our revised safety guidance. The differences between spark, corona and brush discharges are explained. By means of a corona discharge, anyone should be able to discharge a fully charged dome harmlessly by touching the dome with a pointed finger (Fig. 3).

Figure 3 - Corona discharge through a projecting finger.

The operational rules published in Bulletin 205 [1] have been revised. The new ones are on the website. Details on screening for heart conditions are given.

As for the report that the Edulab VDG is frighteningly energetic – so it is, and so it should be. Good for it! What is the point of running your VDG if it doesn't scare? A spark discharge needs just enough energy to be violent, but not too much to injure. How that judgement is made is what our research has found out.

Of the four machines tested (Table 3), the Arco was under par, the Edulab and Frederiksen were suitably scary, but the Altay was right on the edge of what we consider tolerable. The best performer of all was the machine from Frederiksen.

Don't zap your laptop

During spark discharges, electromagnetic energy is radiated from the spark gap. This radiated energy might be picked up by any nearby electrical leads, across which extra-high voltages can be induced. These voltages can destroy electronic apparatus (Fig. 4). Vulnerable equipment includes anything supplied from a plug-top power supply such as a laptop computer, digital balance or digital camera because the long supply lead can act as a pick-up aerial. Keep ICT equipment well away from a VDG.

Van de Graaff	EduLab	Frederiksen
Isolated dome:		
Spark gap to earth (m)	0.075	0.120
Voltage on dome (kV)	188	261
Dome with person attached:		
Spark gap to earth (m)	0.038	0.0475
Voltage on dome (kV)	106	130
Maximum voltage on person (kV)	50	50

Table 2 - Values of voltage on domes with and without person attached.

Maker	Model	Supplier	Product code	Price (£)	Other suppliers
Arco		Economatics	1080660/P	110.00	Timstar
Edulab		Economatics	P920	239.95	S&C
Frederiksen	3700.50	Timstar	EL62550	327.50	PASCO S&C
Altay	4623.20	IDS	withdrawn		

Table 3 - Details of the 4 VDGs reported on.

References

1. *Van de Graaff generator hazards* Bulletin 205 SSERC 2002.
2. BS 5958: Part 1 : 1991 *Code of practice for control of undesirable static electricity Part 1 General considerations* BSI.
3. PD CLC/TR 50404:2003 *Electrostatics – Code of practice for avoidance of hazards due to static electricity* BSI.
4. BS EN 60052:2002 *Voltage measurement by means of standard air gaps* BSI.
5. DD IEC/TS 60479-1:2005 *Effects of current on human beings and livestock – Part 1: General aspects* BSI.

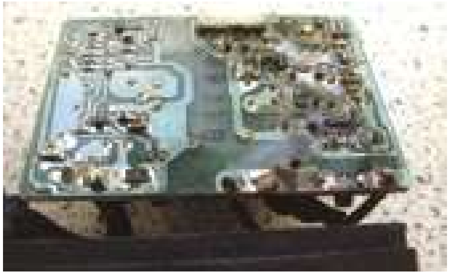

Figure 4 - Track-side view of a plug-top power supply damaged by a VDG spark.