The Cascading Pebble Divertor for the Spherical Tokamak Power Plant

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ABSTRACT
The design of a power plant based on the spherical tokamak (ST) is being developed in order to explore its potential advantages. The plasma is operated in a double null configuration, forming both an upper and lower divertor. In order to accommodate the high erosion rates and heat fluxes developed in the divertors, a system based on a cascading flow of silicon carbide pebbles is being developed. The pebbles flow into the upper divertor where they fall as a toroidal curtain, which intercepts the divertor particle flux. The pebbles then flow under gravity through ducts to the lower divertor where they form a similar curtain. The bulk temperature of the pebbles rises to about 1200°C although the outer surface is transiently heated to about 1800°C. The pebbles pass out of the vacuum chamber into holding tanks and then into a fluidised bed heat exchanger. Here the pebbles are cooled down to about 300°C and dust and damaged pebbles are removed. The pebbles are transferred to an upper tank by a pneumatic conveyor where the remaining gas is removed and the pebbles flow into the upper divertor again.

1. INTRODUCTION
The conceptual design of the ST power plant (STPP) has been previously reported [1,2,3], its main parameters are shown in table 1 and the load assembly is shown in figure 1. This paper presents the current status of the design of the cascading pebble divertor system for this power plant. This system has been developed based on analysis and systems modelling, together with experimental work and manufacturing trials.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma aspect ratio</td>
<td>1.4</td>
</tr>
<tr>
<td>Major radius</td>
<td>3.4m</td>
</tr>
<tr>
<td>Plasma elongation</td>
<td>3.2</td>
</tr>
<tr>
<td>Plasma triangularity</td>
<td>0.55</td>
</tr>
<tr>
<td>Plasma current</td>
<td>31 MA</td>
</tr>
<tr>
<td>Pressure driven current</td>
<td>29.3 MA</td>
</tr>
<tr>
<td>Centre rod current</td>
<td>30.2 MA</td>
</tr>
<tr>
<td>Normalised beta</td>
<td>8.2</td>
</tr>
<tr>
<td>Normalised int. plasma inductance</td>
<td>0.14</td>
</tr>
<tr>
<td>Confinement relative to IPB98(y,1)</td>
<td>1.4</td>
</tr>
<tr>
<td>Safety factor on axis &amp; edge qs, qss</td>
<td>3, 13</td>
</tr>
<tr>
<td>Energy confinement time</td>
<td>2.0 sec</td>
</tr>
<tr>
<td>Electron density : Volume average</td>
<td>1.1x10²⁰ m⁻³</td>
</tr>
<tr>
<td>Central</td>
<td>1.4x10²⁰ m⁻³</td>
</tr>
<tr>
<td>Temperature: Volume average</td>
<td>19.2, 24.0 kV</td>
</tr>
<tr>
<td>NBI current drive power</td>
<td>60 MW</td>
</tr>
<tr>
<td>Total fusion power</td>
<td>3.1 GW</td>
</tr>
<tr>
<td>Net electrical power</td>
<td>1.1 GW</td>
</tr>
<tr>
<td>Average neutron wall loading</td>
<td>3.5 MW/m²</td>
</tr>
</tbody>
</table>

Table 1 Power Plant Parameters

2. THECASCADED PEBBLE DIVERTOR
The design of the divertor of a power plant is particularly demanding due to the high heat fluxes (10’s of MW/m²) and high sputtering rates that limit the performance of conventional solid surface divertors. In order to overcome these two issues it is proposed to apply the cascading pebble divertor concept [2,4] to the ST power plant.

![Figure 1 3D View of STPP](image)

A design of the cascading pebble divertor system is presented here in which the primary divertor target surface is composed of a cascade of pebbles designed to intercept the bulk of the particle energy and allow it to be transported from the divertor as heat in the temperature rise of the pebbles. The pebbles are passed through a fluidised bed heat exchanger, which quickly cools them before they...
can be returned for a further pass through the cascade. The pebble flow enters the load assembly at the top divertor where it splits into two flows. One flow forms a curtain of cascading pebbles across the inboard divertor leg. It then flows, under gravity, through ducts in the inboard shield to the lower divertor, where it again forms a cascading flow across the inner divertor leg before flowing out of the load assembly. The other flow forms a cascading curtain across the upper outboard divertor leg then flows through channels in the steel structure between the blanket modules, to the lower outboard divertor leg. Here it again forms a cascading curtain of pebbles across the particle flux before flowing out of the power core. These emerging pebble flows have a flow rate of about 450 kg/sec and pass into holding tanks which act as air lock chamber pairs. Once one tank is full the flow is directed to the other tank of the pair and the first full tank is isolated from the vacuum chamber, filled with helium gas and its contents flow out into one of two large fluidised bed heat exchangers. These heat exchangers have internal gas cooled, cooling pipes, which extract the bulk of the heat from the pebbles while they are fluidised by a modest flow of low-pressure helium gas.

The high-grade heat removed by the 80 bar helium in the cooling pipes is then mixed with the 80 bar helium gas from the blanket modules which is input to the steam cycle. As the pebbles are cooled they flow to the top of the fluidised bed where they can flow out of the fluidised bed into one of the pneumatic conveyors, which transport the pebbles back to the top of the machine using dense phase slug flow. The pebbles flow into an annular tank where the helium pressure is only about 1 bar. This gas is then pumped away in a multistage pumping system to a central helium storage tank. Finally the pebbles flow under gravity into the top divertor and the cycle repeats. In this way all helium gas is recycled and the number of mechanical moving parts is kept to a minimum which offers high reliability. The system is shown schematically in figure 2.

3 SYSTEM ANALYSIS
3.1 Divertor Power loads
Under steady state conditions the power arriving at the divertor targets is due to the alpha particle power and the neutral beam injected power. It is assumed here that 50% (Krad) of this power can be radiated from the plasma to the first wall by the addition of impurity gases such as argon, as well as Bremsstrahlung radiation. The ST power plant is operated in a double null configuration and it is assumed that 50% (K_D-null) of the power goes to each divertor. This can be achieved by adjustments to the upper and lower PF coils to compensate for the vertical particle drift that would otherwise cause an up/down imbalance.

![Figure 2 Cascading Pebble Divertor Schematic](image)

When operated in the double null configuration the majority of the divertor power goes to the outboard leg of an ST [3]. Experimental evidence from MAST shows that about 95% (Kout) of the power flows to the outboard side (although this varies, depending on the conditions) and a similar split in power is assumed here. The power to each outboard/inboard divertor legs is given by:

\[
Q_{Out/in} = (Q_\alpha + Q_{NBI}) K_{rad} K_{D-null} K_{out/in}
\]

3.2 Estimate of SOL Thickness
In order to evaluate the power density at the targets, an estimate of the mid-plane scrape off layer (SOL) width, h, is required. A number of theoretical models have been assessed by comparing with the MAST L-mode data, and eight “best fit” models survive. These scalings and their h predictions for the collisional SOL cases are described in detail in [3,5] and the average value and its standard deviation for the inner and outer targets are shown in table 2. The SOL widths at the targets can be broader than those at the mid-plane due to the poloidal flux expansion, f, which was estimated from the free-boundary equilibria for the ST power...
The power variation across the SOL at the target is an exponential in which \( f_h \) is the 1/e width. A small part of the power diffuses into the private plasma zone side of the separatrix to form a narrower exponential profile as shown in figure 3. It is assumed here that this private zone exponential has a 1/e width which is 50% that of the main SOL. There is clearly a wide range of predictions from the acceptable models for the SOL widths, and the extrapolation uncertainties are therefore large.

### 3.3 Poloidal and Parallel Power Density

An estimate of the power density incident on a continuous, smooth toroidal surface inclined at an angle \( \theta \) to the poloidal flux can be made assuming the power acts as a top-hat power density profile whose width is equal to the 1.5\( f_h \) at the target. In this case the average poloidal power density is shown in table 2 and given by:

\[
\frac{Q}{A} = \frac{Q_{\text{Out/in}} \sin \theta}{2 \pi R_{\text{Target}} 1.5 \ f_h}
\]

This shows that the power density on the outer leg is much higher than that on the inner leg.

The magnetised plasma in a conventional aspect ratio tokamak normally impinges on the continuous target surface at a shallow toroidal angle, typically 5° due to the ratio of total to poloidal fields. However, in the ST the toroidal field component is relatively low giving a higher toroidal angle, typically 25°. In the case of the cascading pebble divertor, the target is not continuous and the power density experienced by the pebbles is the parallel power density. The ratio of the poloidal to parallel power density is also dependant on the ratio of these field values and is defined as \( \sin A \) in figure 3. i.e.

\[
\sin A = \frac{B_{\text{pol}}}{B_{\text{total}}} = \frac{Q_{\text{pol}}}{Q_{\text{par}}}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Divertor Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner</td>
<td>Outer</td>
</tr>
<tr>
<td>Power flow to each leg, MW</td>
<td>8.5</td>
</tr>
<tr>
<td>Radius of the target m</td>
<td>1.6</td>
</tr>
<tr>
<td>Axial position of target m</td>
<td>8.4</td>
</tr>
<tr>
<td>Average SOL width h mm</td>
<td>55.2</td>
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<tr>
<td>Standard deviation of SOL width</td>
<td>35.1</td>
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<tr>
<td>Radial field component T</td>
<td>0.213</td>
</tr>
<tr>
<td>Axial field component T</td>
<td>0.308</td>
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<tr>
<td>Toroidal field at the target T</td>
<td>3.74</td>
</tr>
<tr>
<td>Poloidal field T</td>
<td>0.375</td>
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<tr>
<td>Total field T</td>
<td>3.759</td>
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<tr>
<td>( B_{\text{pol}}/B_{\text{total}} )</td>
<td>0.10</td>
</tr>
<tr>
<td>( Br/Br_{\text{pol}} )</td>
<td>0.57</td>
</tr>
<tr>
<td>Angle A in deg</td>
<td>5.73</td>
</tr>
<tr>
<td>Surface area of separatrix ( \text{m}^2 )</td>
<td>116.6</td>
</tr>
<tr>
<td>Poloidal flux expansion, ( f )</td>
<td>1</td>
</tr>
<tr>
<td>Poloidal flux for top-hat profile &amp; avg. h on 10° target MW/m²</td>
<td>1.6</td>
</tr>
<tr>
<td>Poloidal flux for top-hat profile &amp; min. h on 10° target MW/m²</td>
<td>4.7</td>
</tr>
<tr>
<td>Peak parallel flux for exponential profiles and avg h MW/m²</td>
<td>25</td>
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<tr>
<td>D⁺ gyro radius mm</td>
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<tr>
<td>T⁺ gyro radius mm</td>
<td>1.05</td>
</tr>
<tr>
<td>He²⁺ gyro radius mm</td>
<td>0.61</td>
</tr>
</tbody>
</table>

**Table 2 Key Parameters used to Determine Pebble Power Density**

Another factor important in considering the power density incident on the cascading pebbles is the gyro radius of the particles in the magnetised plasma. This is a function of their charge \( q \), mass \( m \), speed \( V \) and the magnetic field strength \( B \) and is given by:

\[
r = \frac{mV}{Bq}
\]

Here the speed \( V \) is the mean value of a Maxwellian distribution. The gyro radii for the main plasma
particles are shown in Table 2, assuming an ion temperature of 500 eV. These results show that the ions have a gyro radius that is comparable to the radius of pebbles. This will allow the ions to approach the pebble surface from all directions and has the effect of applying the flux over the full surface area of the pebble, which is 4 times its projected area of \( \pi r^2 \). This effect is complemented by the fact that the pebbles will be rotating as they fall under gravity through the divertor plasma. Hence the power density experienced by an unshadowed pebble as it passes through the peak of the exponential flux profile is given by:

\[
P_{\text{out/in}} = \frac{Q}{12 \pi R_{\text{Target}} h f \sin A}
\]

The parallel power density profiles on the SOL side and private side of the separatrix are given by:

\[
P_{\text{SOL}} = P e^{-y_f h}, \quad P_{\text{Private}} = P e^{-y_{0.5} f h}
\]

### 4 CASCADE FLOW RATE & TRANSMISSION

The free falling pebbles leave the slot in the bottom of the cascade generator with an initial velocity \( u_0 \). The drop height of the pebbles from the slot to the separatrix, \( s \), accelerates them to a velocity \( v \), in a time \( t_1 \). Assuming the vertical distance through the divertor plasma at the target is given by \( H \) then the pebble heating time is \( H/v \) i.e.:

\[
u = \sqrt{\frac{u_0^2 + 2gs}{H}} \quad s = u_0 t_1 + \frac{g t_1^2}{2}
\]

\[
H = \frac{1.5 f h}{\cos B} = \frac{1.5 f h B_{\text{Pol}}}{B_r}
\]

Where \( W \) = mass flow rate of pebbles

\( \rho_B \) = bulk density of the flow

\( b \) = slot width

\( l \) = slot length

Assuming a drop height to the plasma separatrix of 0.8m in the outer leg, which has a pebble flow rate of 450 kg/sec through a 22mm wide slot, gives a pebble initial velocity of 0.65m/sec, a final velocity of 4m/sec and a pebble heating time of 35msec.

Dimensional analysis combined with comparison to fluid flows suggests that the flow rate \( W \) of pebbles through an orifice should be proportional to:

\[
W \propto \rho_B \sqrt{g D_o^{2.5}} = \rho_s (1 - \varepsilon) \sqrt{g D_o^{2.5}}
\]

Where \( \rho_B \) = density of solid material

\( D_o \) = orifice diameter

\( \varepsilon \) = void fraction

However, experimental results carried out by Beverloo et al. [6] show the exponent of \( D_o \) to be greater than 2.5 particularly with large particle diameters. This can be explained by assuming that along the margin of the orifice is a zone, which is less fit for use for the flow. The size of this zone is proportional to the particle size \( d \) so that the flow rate equation becomes:

\[
W \propto \rho_B \sqrt{g (D_o -kd)^{2.5}}
\]

Where \( k \) is a dimensionless constant depending on particle shape and surface properties. The value of \( k \) was determined by Beverloo for a variety of seeds and found to be 1.4 ± 0.1. The effective diameter concept can then be used to develop this formula for various orifice shapes. Beverloo’s data for a rectangular orifice gives:

\[
W = 44.4 \rho_B A' \sqrt{g D_h'}
\]

Where \( D_h' \) and \( A' \) are the effective hydraulic diameter and effective area given by:

\[
D_h' = \frac{4(b-kd)(l-\varepsilon)}{2(l+b+2kd)}, \quad A' = (b-kd)(l-\varepsilon)
\]

In all the tests carried out by Beverloo the diameter of the hopper was large compared to the characteristic dimension of the orifice. This leads to a 3 dimensional re-organisation of the pebbles as they flow towards and into the orifice. However, the systems being evaluated here have a delivery chute or hopper whose length is the same as that of the slot, which leads to a 2 dimensional re-organisation of the pebbles as they enter the slot. To account for these differences in the approach flow conditions a linear scale factor \( C \) was introduced. The full flow equation in SI units is then:

\[
W = 44.4 \sqrt{2} \frac{C}{60} \rho_s (1-\varepsilon) \sqrt{g \frac{(l-\varepsilon)^{\frac{1}{2}} (b-kd)^{\frac{3}{2}}}{\sqrt{l+b+2kd}}}
\]

Here a value of 1.4 is assumed for the constant \( k \). Also, a value of 0.415 is assumed for the void fraction, \( \varepsilon \), based on measurements of the random packing fraction of alumina balls in a cylinder whose diameter is about 40mm i.e. the same as the height of the chute. Note that this is slightly greater than the value of 39% usually quoted for the random packing factor of spheres in containers whose diameter is very large compared to the sphere diameter.

In order to determine the constant \( C \) two test rigs were constructed and a series of tests carried out on each. The first used an inclined chute to deliver the pebbles to the slot at its end. This chute is fed by a vertical pipe 80mm in diameter. This geometry is representative of that needed for a demonstration of the cascading pebble divertor on the MAST ST. Tests on this system used four different pebble diameters, 1.5, 2.3, 3.0, and 2.6mm, two different slot lengths, 300 and 200mm, 3 to 5 different slot
widths, two different ball materials alumina and glass. A further test rig with a vertically orientated hopper was also constructed and for flow rate measurements this is more representative of the geometry proposed for the STPP. Typical results from these tests are shown in figure 4, which show good agreement between the measured flow rates and the modified Beverloo equation developed here.

![Figure 4 Measured and Predicted Flow Rates](image)

5 PEbble THERMAL & STRESS ANALYSIS

An analytical expression for the temperature as a function of radius, \( r \), in the pebble subjected to a uniform heat flux, \( P \), for a time, \( t \), is given by Carslaw and Jaeger [9] as:

\[
T = \frac{3Pt}{\rho_s C_p a} + \frac{P(5r^2 - 3a^2)}{10ka} - \frac{2Pa^2}{kr} \sum_{n=1}^{\infty} \frac{\sin(ra_n/a)}{\alpha_n^2} e^{-\alpha_n^2t/a^2}
\]

Here \( \alpha_n, n=1,2, \ldots \) are the positive roots of \( \tan \alpha_n = \alpha \) and \( \rho, C_p, K, \) and \( \kappa \) are the density, heat capacity, thermal conductivity and thermal diffusivity of the pebble of radius \( a \). The resulting tensile stress generated at the centre of the heated pebble is given by:

\[
\sigma_0 = \frac{2E \alpha}{3(1-\nu)} \left( T_0 - \frac{6Pt}{d \rho_s C_p} \right)
\]

Here \( E, \alpha, \nu \) are the Young’s modulus, thermal expansion coefficient and Poisson’s ratio of the material and \( T_0 \) is the centre temperature rise. These two expressions, which use constant material properties, were used for systems analysis studies to explore the parameters. Once a suitable pebble size had been determined finite element thermal and stress analysis was performed in which the properties change with temperature and the exponential heating rates determined in section 3 were used. The centre and outer surface temperature profiles for an un-shadowed silicon carbide pebble with a 50-micron outer layer of tungsten are shown in figure 6. This shows how the temperature of the outer surface rapidly rises as the pebble passes through the exponential flux profiles of the upper outer divertor leg and then the pebble equilibrates and radiates heat to its neighbours before it passes...
through the lower outer divertor leg. This causes the bulk pebble temperature to drop from 1250 to 750°C. The lower divertor leg again rapidly heats the outer surface of the pebbles to a maximum of about 1800°C before the pebbles reach a thermal equilibrium temperature of 1150°C when they pass into one of the holding tanks. The thermally induced tensile stress at the centre of the pebble is also shown in figure 6 and peaks at 450 and 600MPa on the first and second heating cycle. Although this stress exceeds the tensile strength of the silicon carbide it is a secondary stress that may be relieved as cracks start to form within it. Cyclic tests using lasers to rapidly heat the pebble surface are planned to determine the materials strength under this form of loading.

Figure 6 Transient Temperature & Stress Profiles

6 SPUTTERING OF PEBBLE SURFACES
The ions approaching the pebble target have sufficient energy to eject atoms from the surface by physical sputtering. The rate at which the target material is sputtered by this process, m, is given by:
\[ m = \frac{m_w \sum Y_i x_i P_{DIV}}{N_{AV} 2q_i V} \]
Where \( Y_i \) = sputtering yield from species \( i \)
\( x_i \) = fraction of total ions of species \( i \)
\( P_{DIV} \) = power to the divertor pebble targets
\( V \) = ion temperature assumed to be 500 eV
\( N_{AV} \) = Avogadro’s number
\( m_w \) = atomic mass of target

Since the incoming ions are a mixture of deuterium, tritium, helium and impurity ions, the contribution from each species should be included. An estimate of the sputtering rate is made here assuming:
1 Half the divertor power is carried by the electrons.
2 The ions are accelerated to twice their approach energy when they strike the pebble surfaces by the electric field generated by the electrons.
3 The ions strike the surfaces at normal incidence.
4 The contribution from the impurity ions is small.
5 Plasma composition is 45.8%T, 45.8%D, 8.4%He.

The sputtering yield data given in [10] was used to estimate the sputtering rates which are shown in table 3. This shows that 105 tonnes per year of silicon carbide will be sputtered, which is about 75% of the total mass of the pebbles assuming a total inventory of 2000 million 3.5mm diameter pebbles. If the pebbles have a 50 micron thick tungsten coating then this coating would be sputtered at a rate of 125 tonnes per year and would be completely removed in about 7 months of continuous operation at an 80% duty cycle. Although the total mass of sputtered material is similar for the two cases the volume of material removed is about 6 times less for the tungsten case.

<table>
<thead>
<tr>
<th>Energy eV</th>
<th>Silicon Carbide</th>
<th>Tungsten</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>93.3</td>
<td>30.1</td>
</tr>
<tr>
<td>1000</td>
<td>105.0</td>
<td>33.8</td>
</tr>
<tr>
<td>D Y_i</td>
<td>0.030</td>
<td>0.003</td>
</tr>
<tr>
<td>T Y_i</td>
<td>0.09</td>
<td>0.007</td>
</tr>
<tr>
<td>He Y_i</td>
<td>0.125</td>
<td>0.015</td>
</tr>
<tr>
<td>( \Sigma Y_i x_i )</td>
<td>0.005</td>
<td>0.009</td>
</tr>
<tr>
<td>Tonnes/yr</td>
<td>62.3</td>
<td>124.8</td>
</tr>
<tr>
<td>m³/year</td>
<td>3.2</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Table 3 Sputtering Analysis Results

7 FLUIDISED BED HEAT EXCHANGER
The main component of the external pebble handling, cooling and transport systems is the fluidised bed heat exchanger shown in section in figure 7. The hot pebbles, ≈1150°C, are driven from the holding tanks into the lower end of the main annular chamber where they first mix with cool fluidising helium gas. This reduces the pebble temperature to ≈1000°C before the pebbles pass over the internal array of cooling tubes. These tubes contain helium gas at 80 bar with an inlet temperature of 300°C and an outlet temperature of 600°C. This counter-flow arrangement cools the pebbles and the fluidising gas down to about 340°C by the time they reach the top of this chamber, from where they are transported by six pneumatic conveyors to the top of the power core. The dust generated by sputtering of the tungsten surfaces may become weakly attached to adjacent pebbles and be carried into the fluidised bed. Here the attrition between the pebbles will remove the dust and it will be carried by the fluidising gas flow to the top of the chamber. This dust laden gas flow then passes through inclined mechanical filters, which remove the bulk of the dust, which is collected in an annular chamber at the base of the filters. A gas circulator
driven by a helium turbine provides the fluidisation gas flow. This is incorporated into the base of the chamber, which removes the need for rotating seals.

Figure 7 Fluidised Bed Heat Exchanger

8 PEbble MANUFACTURING TRIALS
In order to demonstrate the manufacturing feasibility and estimate the production costs some pebble manufacturing trials were carried out. Two different types of silicon carbide were investigated: pressed and sintered from powder (Hexalloy SA) and reaction bonded (REFEL). Although initial trials of both were successful the REFEL material proved more difficult to manufacture and also has a lower maximum operating temperature of 1400°C due to the melting point of the silicon used to infiltrate the silicon carbide. The pressed SiC manufacturing process leaves a belt around the equator of each pebble, which must then be ground off. The tungsten coating process has been successfully demonstrated and the process parameters have been optimised based on a chemical vapour deposition process. A micrograph showing the section through a coated pebble is shown in figure 8.

Figure 8 Section through W Coated SiC Pebble

9 SUMMARY AND CONCLUSIONS
The high heat flux and erosion rates in power plant divertors has led to consideration of a cascading pebble divertor system in which the silicon carbide pebbles, coated in tungsten, are re-circulated through the power core. This system is particularly suited to the ST due to its relatively low parallel power density and offers the advantages of a solid tungsten surface that is continuously replenished. Systems analysis coupled with experimental work and manufacturing trials have been used to develop the design. Further work is needed to improve confidence in the prediction of the divertor power densities and further development of the systems and components is required to demonstrate their performance.

The ST power plant study, together with data from the MAST and NSTX experimental programmes, continues to show that the ST is a strong candidate for future economic power generation.

References
8 “Transmissivity of a falling pebble curtain for nuclear fusion reactors”, S.E. Johnson et al. 7th World Congress of Chemical Engineering, 2005, Glasgow, Scotland.

Acknowledgements: This work is jointly funded by the UK Engineering and Physical Sciences Research Council and by EURATOM.