Storage & Handling Risks When Co-Firing Coal & Solid Biofuel

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SYNOPSIS

Currently the UK's thermal power generation industry is experiencing considerable change largely brought about by an environmentally driven move away from coal as a single source fuel to co-firing with solid biofuels.

The current most problematic area appears to be with the fifteen main line power stations, generating about 27,000 Mw, owned by Scottish and Southern (Ferrybridge C & Fiddlers Ferry), British Energy (Eggborough), Drax Power (Drax), EdF Energy (Cottam & West Burton), International Power (Rugeley), Powergen (Ironbridge, Kingsnorth & Ratcliffe), RWE Npower (Aberthaw, Didcot A & Tilbury) and Scottish Power (Longannet and Cockenzie). It is understood that some of the stations are operating on a commercial basis handling citrus, olive residue, palm nuts, shea, sewage sludge and wood. Other stations are believed to be conducting or planning trials with cereal, cereal residues, energy crops, forestry/sawmill wastes, milled palm nuts, olive residues & wood.

There are a limited number of basic options available for the direct co-firing of solid biofuels at coal-fired power stations. These are (i) Pre-blending of the solid biofuels with coal and the feeding of the blended fuel into the unit bunkers and thence on to the boiler via existing coal milling and firing equipment, (ii) Installation of new solid biofuel storage bunkers plus feeding system and modification of existing coal mills on a given unit to allow milling of the solid biofuels and the firing of these into the boiler via existing coal firing equipment and (iii) Installation of new solid biofuel storage bunkers and feeding system plus new dedicated solid biofuel milling equipment on a given unit and the introduction of the milled fuel into the existing coal firing system

The coal handling plant at all of the above mentioned stations were designed more than 30 years ago. Coal is a well known fuel and its physical and flow properties are well defined to ensure acceptable, and in some situations extremely good, designs for the necessary materials handling plant and equipment up to the mills and boilers.

This paper examines the downside risks associated with (i) coal/solid biofuels mixtures that are more difficult to handle than coal alone, which may result in a reduction of free flow capability in the existing design of unit bunkers and (ii) solid biofuels, whose physical and flow property basis for free flow bunker design is hardly known resulting in a highly probable reduction of anticipated free flow capability in the storage bunkers that are currently being built.

1. INTRODUCTION & BACKGROUND

In July 1980, the British Steel Corporation (BSC) published "A Design Guide for Mass Flow Bunkers and Silos" (1). The information contained in this report was at the heart of the many bunker design seminars held by BSC's Bunker Design Advisory Service (BDAS) during the 1970's. Mass flow is defined as "all particles moving on feeder start-up with slip at the walls everywhere".

Over the 7-year period from 1973, the BSC's BDAS measured the flow properties of about 70 coals including 11 from Australia, Poland, South Africa and the United States of America and determined the mass flow geometry of a range of storage bunkers and silos.

In the 1980 BSC publication mentioned above, the following "average" data was given for guidance in the design of mass flow coal bunkers/silos as indicated below:-

Effective Angle of Internal Friction (δ)	Surcharge Wall Friction for Steel/Concrete Lining (φ')	Cone Wall Friction for Glass Lining (φ')	Bulk Density (t/m^3)
55°	30°	14°	0.90

Table 1 BSC Flow Property Data Based on 70 Coals

Minimum Wall Slope or Valley Angle (θ)	Diameter or Side of Square Outlet (m)	Sides of Rectangular Outlet (m)
70°	1.85	1.0 x 2.0

Table 2 BSC Bunker Design Data Based on 70 Coals

Care should be taken when using the above data as time storage and impact-filling conditions may require larger outlet dimensions with the coals currently available for purchase on the world market.

In the 1960's and 70's, a roughcast glass lining was favoured by the National Coal Board (NCB) for coal storage bunkers and silos and this was also a fairly standard practice in the BSC and the Central Electricity Generating Board (CEGB).

Nowadays, the most popular wall linings are (i) 2B stainless steel with surface roughness (Ra) < 0.5 micron and (ii) UHMW polyethylene produced from 100% Hostalen GUR powder.

2. AN APPRAISAL OF UNIT BUNKER OUTLET DESIGNS AT UK POWER STATIONS

All of the bunkers at the fifteen main line stations referred to in the Synopsis have suffered flow problems from time-to-time. However, in January 1992, an independent survey at the then National Power - Drax power station provided a useful opportunity in the UK to evaluate the benefits of flow property measurement when applied to the storage and handling of coal in unit bunkers.

Implementation of key recommendations was fast, leading to a coal handling investigation on a wide range of UK coals expected to be burned in the future. The benefits of flow property measurement were major, allowing retrofit/new unit bunker designs to be made which improved flow and reduced coal flow failures at the station's bunkers. The retrofit flow improvement concepts that started at Drax were soon applied and extended to other UK stations (2, 3)

At all the main line stations referred to earlier, coal is extracted from the unit bunkers via slotted outlets varying in width from about 620mm up to 900mm with slot lengths at about 3m long. As these unit bunkers are all about 30 years old, none were designed for mass flow, which, according to Table 2 above required a minimum 1.0m slot width based on BSC's flow property testing of 70 coals.

3. THE MOVE TO ALTERNATIVE FUELS AND CO-FIRING IN UK POWER STATIONS

The final paragraph in Section 4.4 (Bulk Solid Samples) of the British Steel Corporation publication "A Design Guide for Mass Flow Bunkers and Silos" (1) states the following:-

"Where a blended mix of inert bulk solids is to be stored, experience has shown that the cohesiveness of the blend does not exceed that of its worst constituent. This fact may reduce the number of samples that have to be tested".

Some two and a half decades on from the publication of this useful guide, it is the author's belief, based again on experience, that a blended mix of certain powder and bulk material constituents can exceed the cohesive strength of the individual components.

The initial example of this was with regard to the addition of as little as 5% of dry ground coke breeze to wet coking coal which was beneficial in decreasing the coke's friability in handling. A typical coal bunker outlet of say 1m diameter would need to increase by 50% to 1.5m diameter to guarantee free flow with the coal plus the small percentage of fine breeze additions.

The use of pet-coke as an alternative fuel was pioneered in the UK largely by the cement makers. In the late 1990's flow property assessments made on a few coal/petcoke mixes revealed that as little as a 10% addition of petcoke could cause the handleability ranking of the mix to be worse than the original coal. It is reported that field trials to assess the boiler combustibility of the mix also indicated that the unit bunker storage plant experienced increased coal-flow failures resulting in blockages.

4. THE METHODOLOGY OF HANDLEABILITY APPRAISAL FOR FUELS

The methodology used to determine the handleability ranking of (i) coal, (ii) coal/alternative fuel mixes and (iii) alternative fuels is based on the determination of a new flow blockage parameter pioneered and developed by Dr H Wright & Associates (HWA) based on the theories of Dr Andrew W Jenike.

The Jenike technique involves packing and shearing the material to determine its cohesive yield strength in a 95.3mm dia. x 34.9mm deep split - ring shear cell under a range of pressure conditions likely to occur in any bin, hopper, bunker or bunker during filling or flow.

A fairly quick evaluation of changes in cohesive strength is determined via measurement of the instantaneous unconfined yield strength (fc). This parameter is the yield strength of the compacted material at the free surface of an arch in a bunker or silo. It is a measure of the cohesion/frictional and agglomerating tendency of the material.

Since 1992, beginning with the flow property testwork for National Power – Drax on power station coals, HWA have developed an in-depth Handleability Ranking system for coals and coal/alternative fuel mixes. This is based on an assessment of eight flow properties/mass flow design parameters. Over these 12 years, Handleability Rankings have been produced on this basis for a total of 53 coals and coal/alternative fuel mixes for three major UK generators and one UK cement producer.

Over the last two decades HWA have also developed a simplified shear cell testing methodology which incorporates the use of a standard consolidation (or compaction) load of about 7.5 kN/m^2. This load when used in the Jenike shear cell generally represents the stress consolidation conditions at the outlet of an industrial bunker or silo and is equivalent to about 1.1 psi. Flow property data for over 200 coals in the HWA database is now amenable to the simplified Handleability Ranking system.

The key flow property parameter evaluated in this new Unit Bunker Handleability Ranking system is the unconfined yield strength (fc) kN/m^2 (see Figure 1). This parameter is determined from yield loci shear tests. This strength is used to size the bunker outlet so that the arch collapses under its own weight.

The necessary outlet size for free flow in bunker/silos and choke fed chutes is based on the flow properties of the stored material whilst in a dynamic stress state (i.e. having moved or moving), and is the minimum outlet size required to avoid arching for this condition. It is the diameter of a circular outlet or the width of a slot outlet. Time storage, usually 24 hours with coal, generally gives an increase in yield strength requiring a larger bunker outlet size.

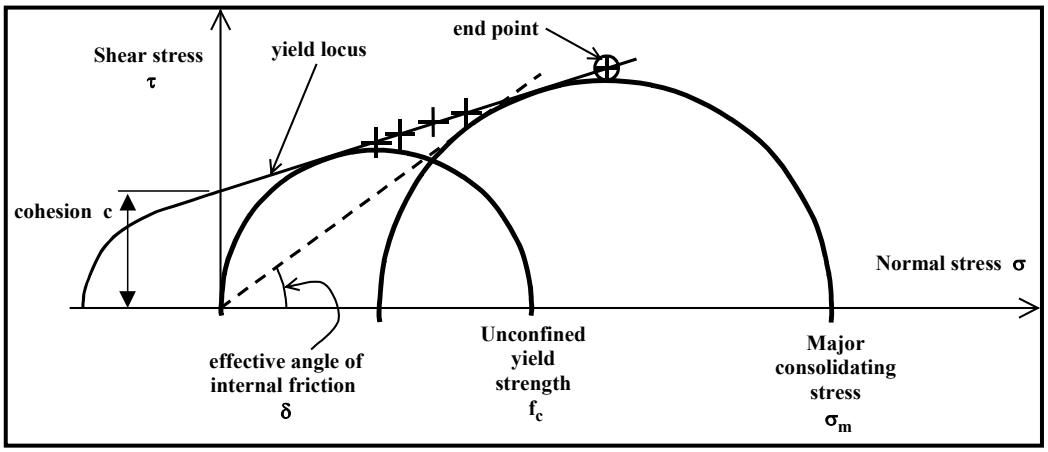


Figure 1 Typical Yield Locus

The outlet size is determined from the Jenike formula:

$$\text{Bunker Outlet Size (D)} = \frac{fc\ H(\Theta)}{\gamma\ K}$$

where f_C is the critical design value for the instantaneous or time storage unconfined yield strength obtained from the Jenike flow functions (FF) generated via the yield loci shear tests referred to previously, γ is bulk density and $H(\Theta)$ is a safety factor to ensure that enough arch weight is available for arch destruction. (NB. Some of the potential arch adheres to the walls and its full weight is not available for arch destruction). $H(\Theta)$ is around 2.4 for conical flow and 1.2 for plane flow. K converts to inches or millimetres.

With slotted bunker outlets an aspect ratio of length/width should not exceed 2.5:1

If Constant C = the ratio of $H(\Theta)/K$, then the diameter or slot width of a bunker or silo outlet becomes a function of the strength to density ratio (SDR):

$$\text{Bunker Outlet Size (mm)} = fc/\gamma . C = SDR . C$$

Where Constant C is generally estimated at:

C = 337 for a circular mass flow outlet and 169 for a slotted mass flow outlet

C = 674 for a circular core (or funnel) flow outlet and 337 for a slotted core flow outlet

5. VALUES OF SDR FOR A RANGE OF COALS & COAL MIXES

The instantaneous unconfined yield strength has been determined from a yield locus consolidated at 7.5kN/m^2. The moisture contents indicated are the critical or most cohesive as determined by moisture/strength evaluations.

It is important to know that time storage usually increases the value of the unconfined yield strength (fc) and, therefore, the size of the outlet. Furthermore, impact arching when filling into an empty bunker can further increase fc.

The above comments also apply to Table 4

Coal & Coal/Alternative Fuel Mix	Instantaneous Strength/Density Ratio (SDR)
Coal 1 (UK) @ 12% Moisture	4.571
Coal 1 (UK) + 10% Overseas Petcoke 1	3.630
Coal 1 (UK) + 20% Overseas Petcoke 1	3.272
Coal 1 (UK) + 10% Overseas Petcoke 2	4.730
Coal 1 (UK) + 20% Overseas Petcoke 2	3.900
Coal 2 (Overseas) @ 23% Moisture Content	3.472
Coal 2 + 10% Wood Pellets (-2mm)	3.970
Coal 2 + 10% Milled Palm Nut (-2mm)	3.510
Coal 3 (Overseas) @ 22% Moisture Content	2.466
Coal 3 + 10% Saw Mill Wood Fines (-2mm)	4.563
Coal 3 + 10% Cereal C P Pellets (-2mm)	4.900

Table 3 Strength/Density Ratios for a Range of Coals and Coal/Alternative Fuel Mixes

6. VALUES OF SDR FOR A RANGE OF SOLID BIOFUELS

Solid Biofuels	Instantaneous Strength/Density Ratio (SDR)
Wood Pellets (-2mm) @ 2% Moisture	2.258
Milled Palm Nut (-2mm) @ 2% Moisture	4.153
Cereal C P Pellets (-2mm) @ 2% Moisture	4.836

Table 4 Strength/Density Ratios for a Range of Solid Biofuels

7. CO-FIRING & SOLID BIOFUEL FIRING – THE DOWNSIDE RISKS

As stated in Section 4 of this paper:-

$$\text{Bunker Outlet Size (mm)} = \text{SDR} \cdot C$$

Where Constant C is generally estimated at:

C = 337 for a circular mass flow outlet and 169 for a slotted mass flow outlet

C = 674 for a circular core (or funnel) flow outlet and 337 for a slotted core flow outlet

In Table 5 the unit bunker slot width for zero time storage has been calculated using the values SDR given in Table 4 and the value of C given above for a mass flow design. The Handleability Ranking is also given with the most difficult to handle material ranked number 1 and the easiest ranked 14th.

Coal, Coal/Alternative Mixes & Solid Biofuels	Slot Width (mm) Zero Time Storage	Handleability Ranking
Coal 3 + 10% Cereal C P Pellets (-2mm)	828	1
Cereal C P Pellets (-2mm) @ 2% Moisture	818	2
Coal 1 (UK) + 10% Overseas Petcoke 2	800	3
Coal 1 (UK) @ 12% Moisture	773	4
Coal 3 + 10% Saw Mill Wood Fines (-2mm)	771	5
Milled Palm Nut (-2mm) @ 2% Moisture	702	6
Coal 2 + 10% Wood Pellets (-2mm)	671	7
Coal 1 (UK) + 20% Overseas Petcoke 2	659	8
Coal 1 (UK) + 10% Overseas Petcoke 1	614	9
Coal 2 + 10% Milled Palm Nut (-2mm)	593	10
Coal 2 (Overseas) @ 23% Moisture Content	587	11
Coal 1 (UK) + 20 % Overseas Petcoke 1	553	12
Coal 3 (Overseas) @ 22% Moisture Content	417	13
Wood Pellets (-2mm) @ 2% Moisture	382	14

Table 5 Minimum Mass Flow Slot Width for Zero Time Storage for a Range of Coals, Coal/Alternative Fuel Mixes & Solid Biofuels

As previously stated, at the main line stations referred to earlier, coal is extracted from the unit bunkers via slotted outlets varying in width from about 620mm up to 900mm with slot lengths of about 3m. To cater for the cohesive overseas coals handled nowadays, (i) at least 40% of these stations have been fitted with flow improvement inserts in the bunker outlet feeder zone and (ii) about 60% have fitted new low friction 2B stainless steel or low adhesion UHMW polyethylene wall linings to improve flow. It is reported that at Kingsnorth, the acquisition of a gravimetric feeder is providing mass flow.

The slot width outlet sizes given in Table 5 are for the instantaneous or zero time storage condition. A private survey on 112 coals (26% from overseas) carried out by HWA in 1984 indicated that, on average, the slot width for 24 hour of time storage was 1.4 times greater than the instantaneous (zero time storage) value.

Assuming 24 hour of time storage and using the multiplier of 1.4 (i) 57% of the fuels listed above would be at risk immediately at the station having unit bunkers with 900mm slot widths and (ii) 86% of the fuels listed above at the station having unit bunkers with 620mm slot widths.

As indicated in Table 2, the 1980 BSC guidelines, based on the flow properties of 70 coals, slot outlet dimensions of 1m x 2m are recommended for mass flow bunkers. As the diagonal of this outlet is some 2.236m, the Jenike design method implies that there is some allowance for 24 hour of time storage. Generally this is limited to an increase of about 20% on the instantaneous (zero time storage) condition.

Certainly, the slot lengths of around 3m, found at almost all power stations, should ease somewhat the 57% and 86% risk factors listed above. However, when slot length/width aspect ratio advances beyond 2.5:1 (at a slot width of 620mm the aspect ration is 4.9:1), ratholing from one end of the slot increases and becomes a serious problem leading to potential blowbacks from the mill.

8. SIMPLIFIED ANALYSIS OF RESULTS

Figures 2 – 7 demonstrate, in a simplified form, the downside risks of unit bunker flow blockages associated with (i) six coal/solid biofuels mixtures of which five are more difficult to handle than the coal alone and (ii) three solid biofuels (i.e. wood pellets, milled palm nut and cereal co-product pellets), of which two are more difficult to handle than the coal alone.

It should be noted that the Jenike flow property tests and geometric mass flow bunker design parameters determined for the three solid biofuels referred to above were all based on using the minus 2mm fraction at 2% free moisture. Whilst the mass flow geometric design data derived assumes that the whole of the bunker contents are sized at minus 2mm, it should also be noted that tests carried out in the late 1960's indicate that as little as 5% fines additions can cause the bunker to behave as if it contained 100% of the fines additions (4).

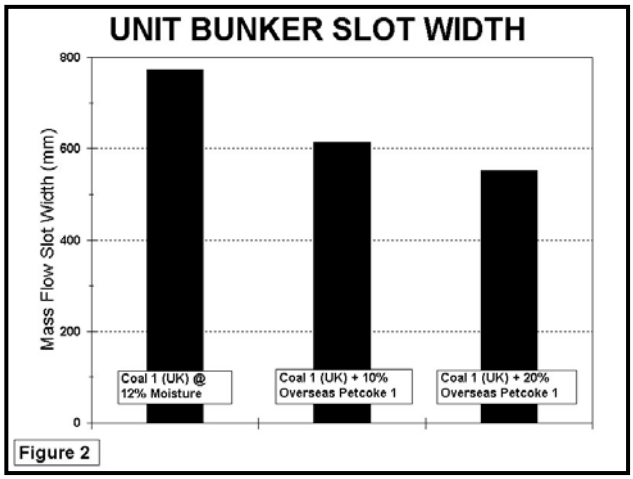
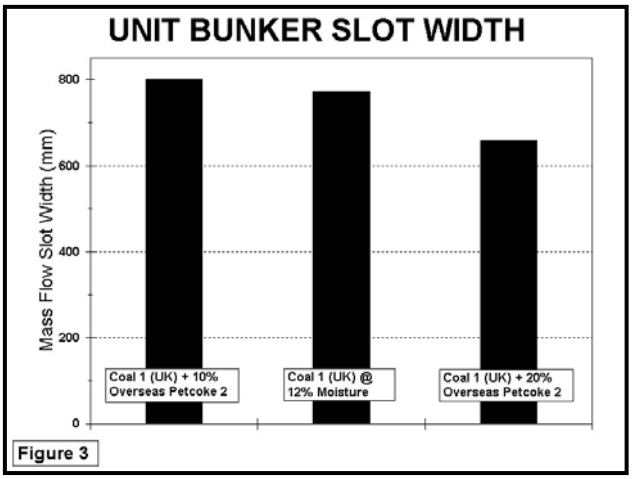


Figure 2



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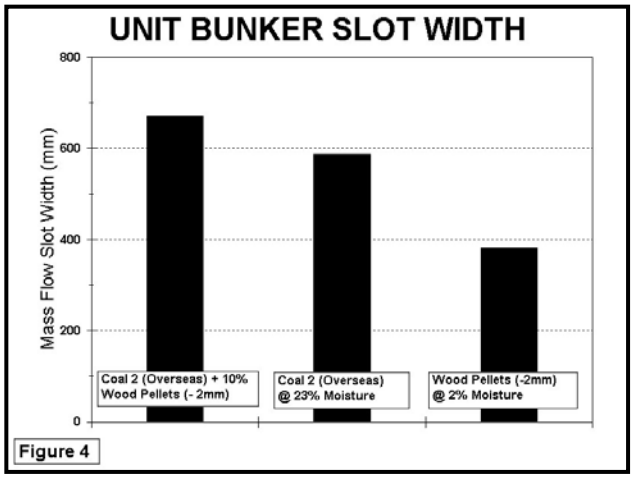


Figure 4

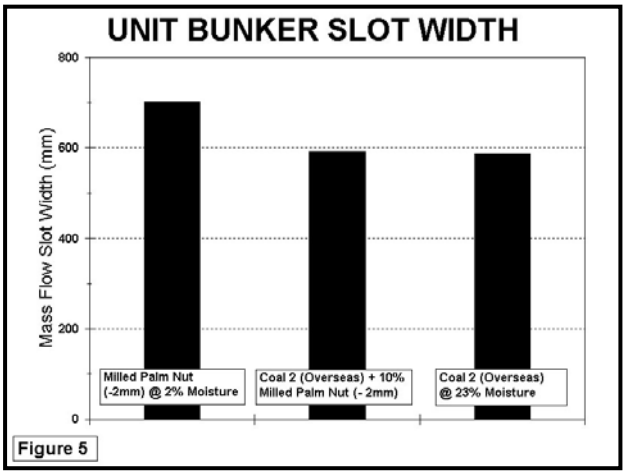
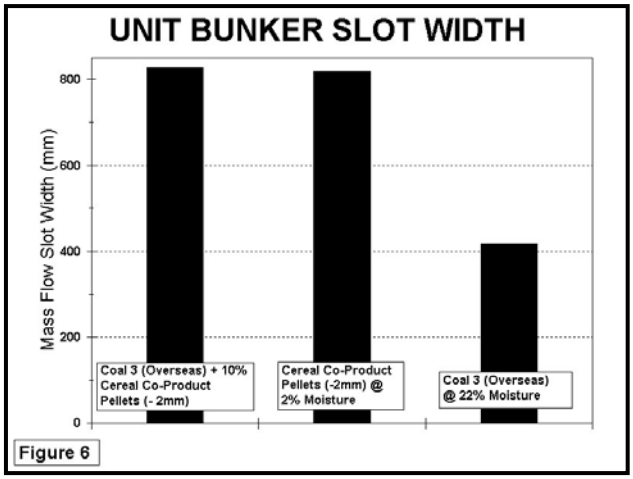


Figure 5



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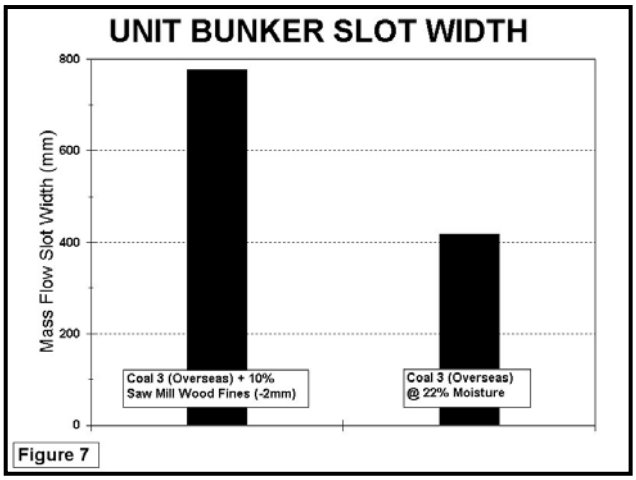

Figure 7

9. CONCLUSIONS

1. Since 1992, Handleability Rankings based on the use of eight flow properties/mass flow design parameters, have been produced for a total of 53 coals and coal/alternative fuel mixes for three major UK generators and one UK cement producer.

2. Recently a new and simplified handleability ranking method has been derived for bunkers and silos. This is based on the strength/density ratio (SDR) of a powder or bulk material utilising the unconfined yield strength (fc).

3. The flow property testwork outlined in this paper, which allows the determination of an SDR Handleability Ranking, has clearly demonstrated that there is a substantial downside risk of blockages associated with the storage of (i) coal/solid biofuel mixes and (ii) solid biofuels, in existing coal fired UK power station unit bunkers.

4. Figures 2 – 7 demonstrate, in a simplified form, the downside risks of unit bunker flow blockages associated with (i) six coal/solid biofuels mixtures of which five are more difficult to handle than the coal alone and (ii) three solid biofuels (i.e. wood pellets, milled palm nut and cereal co-product pellets), of which two are more difficult to handle than the coal alone.

5. At the fifteen main line stations referred to earlier, coal is extracted from the unit bunkers via slotted outlets varying in width from about 620mm up to 900mm with slot lengths of about 3m.

   Using the multiplier of 1.4 to derive 24 hour time storage estimates, of the fuels listed in Table 3 and 4 (i) 57% would be at risk at the station having unit bunkers with 900mm slot widths and (ii) 86% of the fuels listed above at the station having unit bunkers with 620mm slot widths.

6. The three generating companies out of eight who have handleability ranking tables, for some of the coals they burn, are encouraged to pursue further flow property testing of (i) coal/solid biofuel mixes and (ii) solid biofuels. The five generators who have not yet moved into this area should give serious consideration of the obvious benefits that are available.

10. REFERENCES

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