Analysis of machinery breakdowns in power plants fed by biomass and MSW

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1. Introduction

In the past ten years, the use of renewable energy for electricity production has been of great interest, and both the number of power plants and the total installed power generation capacity have been significantly increasing.

This growing interest is mainly related to the need of reducing carbon dioxide emissions and fossil fuels consumption, as the most important countries already agreed in 1990 through the Kyoto protocol.

To increase economical competitiveness of these renewable energy power plants, many subsidies, such as in Italy the CIP 6/92, the green certificates and the *conto energia* have been introduced.

In this paper, power plants fed by solid biomass, biodiesel, biogas and municipal solid waste (MSW) have been considered. In all these cases, energy conversion is obtained through a thermodynamic process.

As reported by the Italian agency promoting renewable energy sources (GSE, 2012), in Italy, from January 1, 2000 to June 30, 2012, 4,832 power plants got the Impianti Alimentati da Fonti Rinnovabili (IAFR) qualification (power plants fed by renewable energy): 41 per cent of these plants are fed by solid biomass, liquid biofuel, biogas and solid waste, corresponding to 29 per cent of the power capacity and generating 51 per cent of the total electricity produced.

The term biomass indicates organic compounds formed of various substances characterized by different physical properties. As a result, the great differences of the bio-raw material affect the thermodynamic process, leading to a high number of different energy conversion technologies.

In this report, the following energy conversion systems, which are considered to be the most diffused and interesting ones, have been analyzed:

- the combustion of solid biomass or municipal waste in steam generators, producing electricity through steam turbines (Rankine cycle); and
- the combustion of biogas or biofuel in reciprocating engines (Otto or Diesel cycle).

In the scientific literature, there is a lack of studies about faults in thermal power plants fed by these fuels. Some information about biomass plants failures is available (Wiltsee, 2000), while limited analysis of faults of reciprocating engines fed by biofuels is reported (Basinger *et al.*, 2010; Hossain and Davies, 2010).

In this work, 23 faults have been analyzed: although they are a limited number and are not a statistic sample (moreover, considering the various plants typology), the study provides significant information that can be of interest for the management of insurance companies, banks and energy utilities.

Data used in this work refer to loss assessments and failure investigations carried out during insurance claims. While the property damage appraisal is always performed, the loss of profit estimation is available only in the presence of a business interruption insurance policy.

2. Power plants classification

In this paragraph, the power plant categories previously introduced are briefly described: in the first case, electricity is produced through a steam turbine and in the second one through a reciprocating engine.

2.1 Steam generator and turbine

In this technology, the fuel is typically solid biomass (such as remains from the wood industry, from farms or from forest pruning) or MSW.

The raw material is burnt in the boiler, and the resulting heat is used to feed a steam Rankine cycle or a more innovative organic Rankine cycle. The mechanical power is obtained through the expansion of the working fluid vapor in the turbine.

The capital cost of these power plants varies between €2,000 and 3,500/kW_{el} (when the gross power plant capacity is around 15-20 MW_{el}) and €7,000/8,000/kW_{el} (100-500 kW_{el}) (Marchesi *et al.*, 2010).

The unit contribution margin strongly depends on government subsidies, electricity price and biomass cost, and it can be roughly estimated in €0,08/0,15 €/kWh_{el}.

These plants typically operate around 8,000 hours per year (they are shut down only in case of maintenance or breakdown).

2.2 Reciprocating engines

In this category, power plants fed by biogas and liquid biofuel have been grouped. In the first case, the four-stroke reciprocating engine operates through a spark-ignited Otto cycle, while in the second one, depending on the fuel, through a spark-ignited Otto cycle or a self-ignited diesel cycle.

In both cases, engines are properly modified by manufacturers to take into account the different specifications of biogas and biofuel compared to the conventional fossil ones.

The capital cost of these power plants typically varies from €1,000 to 3,000/kW_{el}, depending on the power plant capacity and on the fuel type. Costs of landfill biogas production system or of anaerobic digester are not included (Marchesi *et al.*, 2010).

As already described in the previous paragraph, unit profit strongly depends on government subsidies, electricity price and biogas/biofuel cost. In this case, incomes depend also on the possibility of selling heat. In fact, the cogenerative configuration is particularly suitable and recommended due to the limited power capacity of the reciprocating engines, leading to the possibility of selling the whole produced heat.

The unit contribution margin varies significantly, and it can be around €0,20/kWh_{el} (biogas from landfill in case of Italian subsidies) or slightly positive in case of biofuel such as pure plants oil.

Power plants fed by landfill gas are designed to operate continuously. It should be specifically mentioned that the landfill capacity gradually reduces, bringing down the biogas production and, as a consequence, the electricity generation. Therefore, the average yearly operating hours continuously decrease, until the power plant is definitely shut down.

In addition, biogas/biofuel power plants should operate without interruptions. Anyway, at present, due to the rising biodiesel prices, many plants built in the past years do not operate because of the negative profit.

3. Methodology

Referring to the data shown in Table I, hereinafter the meaning of each term, the reported information and the adopted analysis methodology are described.

3.1 Type of power plant

As previously reported, power plants are divided in two categories: in the first one, energy conversion takes place through a Rankine cycle in a biomass boiler and in a steam turbine (biomass and MSW), and in the second one, in an Otto or Diesel cycle reciprocating engine (landfill biogas and biofuel).

3.2 Plant construction year, plant revamping year and faulty component manufacturing year

The plant construction year identifies the completion of the power station erection and its first start up. Instead the plant revamping year, when reported, indicates the date of the last plant refurbishment (such as the substitution of engines, turbines, boilers, etc.).

Finally, the manufacturing year of the faulty component is reported. Typically, it coincides with the power plant construction or revamping one (in case of component substitution during power plant renovation). If the faulty component is a used unit, it can be older than the power station (case number 11, 12, 15 and 17 in Table I).

Table I.
Main data of the analyzed power plants faults

Number	Fault year	Power plant	Erection year	Revamping year	Faulty component manufacturing year	Total power capacity [MW]	Unit power capacity [MW]	Reparation time [days]	Actions to reduce reparation time	Faulty component	Property damage [€]	Loss of profit [€]	Classification of cause of loss
Power plants fed by solid biomass and MSW													
1	2012	Incinerator	2011	–	2011	36	13	21	–	Boiler – superheater	65,500	1,488,300	Erection/construction
2	2012	Incinerator	2011	–	2011	36	13	10	–	Boiler (more parts)	59,200	766,300	Erection/construction
3	2012	Biomass	2002	–	2002	13	13	365	Rental generator	Current generator	550,000	4,934,000	Operation
4	2011	Biomass	2010	–	2010	33	6,3	0	–	HCl tank	10,300	–	Erection/construction
5	2011	Biomass	2010	–	2010	33	6,3	21	–	Cyclone filter	58,700	321,300	Design
6	2011	Biomass	2010	–	2010	33	6,3	30	Manpower	Biomass feeding system	66,900	31,900	Design
7	2010	Biomass	2002	–	2002	14	14	180	Temporary reparation	Turbine gear box	244,000	3,713,100	Operation
8	2009	Incinerator	1995	2003	2003	4	2,6	180	Temporary reparation	Boiler – superheater	508,100	–	Operation
9	2009	Incinerator	2009	–	2009	19	19	20	–	Boiler – evaporator	99,400	–	Erection/construction
10	2006	Incinerator	1995	2003	2003	4	2,6	20	–	Current generator (stator)	26,900	–	Operation
11	2006	Incinerator	1999	–	1972	3	3	10	Temporary reparation	Steam turbine	83,500	89,500	Operation
12	2006	Incinerator	1999	–	1972	3	3	120	Temporary reparation	Steam turbine	675,800	148,000	Operation
13	2006	Incinerator	1995	2003	2003	4	1,4	70	–	Steam turbine	194,600	–	Operation
14	2005	Incinerator	1995	2003	2003	4	1,4	15	–	Exhaust flue gas ducts	49,100	–	Operation
15	2004	Biomass	2004	–	1970	2	2	180	–	St. turbine/Generator	1,520,100	–	Erection/construction
16	2004	Incinerator	2002	–	2002	8	8	45	–	Boiler–Refr. coating	399,000	–	Management
17	2004	Biomass	2004	–	1970	2	2	60	–	Steam turbine	443,300	–	Erection/construction
Power plants fed by biogas and liquid biofuel													
18	2012	Landfill biogas	1995	2004	2004	2	1	60	Other installed engine	Medium voltage switch	100,000	120,000	Management
19	2012	Landfill biogas	2004	–	2004	3	1	30	Other installed engine	Engine – turbocharger	170,000	–	Operation
20	2010	Landfill biogas	2004	–	2004	3	1	10	Other installed engine	Engine – exhaust collector	37,100	–	Management
21	2009	Palm oil	2008	–	2008	1	1	43	–	Palm oil tank	54,600	–	Design
22	2009	Landfill biogas	2004	–	2004	3	1	180	Other installed engine	Engine – pistons, shaft, etc.	234,900	–	Operation
23	2008	Landfill biogas	2005	–	2005	1,6	0,8	20	Other installed engine	Engine – heat exchanger	23,600	27,000	Erection/construction

3.3 Total and unit power plant capacity

The total power plant capacity is the gross electric capacity of the whole plant. If the plant is divided in several units that can operate independently, the unit power plant capacity denotes the one in which the faulty components are installed.

3.4 Property damage

The property damage that has been assessed in all the 23 analyzed cases is equal to the reparation cost of the damaged components. Property damage assessments have been increased by an annual percentage rate to make them comparable, as described in Section 3.6.

3.5 Loss of profit

Details about loss of profit are available only in a limited number of cases (case number 10 of 23). The amount includes losses related to lower contribution margin and higher operating costs, and it has been increased by an annual percentage rate as described in Section 3.6.

3.6 Inflation correction

The loss assessments described in Sections 3.4 and 3.5 have been index-linked to inflation and updated to 2012, making them comparable to each other (damages occurred between 2004 and 2012).

Values reported in Table I have been calculated through the following formula:

$$C_{2012} = C_y(1 + 3.5\%)^{2012-y}$$

where, C_{2012} is the amount referred to year 2012 and C_y is the cost referred to the year of the accident denoted as y.

3.7 Power plant reparation time

The power plant reparation time is the time required to definitely repair the damaged components. That period does not include possible delays related to company management decisions (for example, when plant improvements are performed during components reparation) or actions to reduce the reparation time (see the text in the following).

3.8 Actions to reduce reparation time

This term refers to actions that have been carried out to reduce or avoid power plant stop during components reparation.

If no actions are put into effect, the power plant (or the unit) keeps stop until the end of the reparation. Contrary, for example, in case of rental component or temporary reparation, the power plant can operate, maybe at lower load.

3.9 Classification of cause of loss

To compare damages, a simplified classification based on the cause of loss has been done, as reported in the following:

- *Erection/construction:* The damage is clearly caused by an event occurred during the power plant construction period. For example, a wrong tube welding, an erroneous concrete casting or an improper mechanical alignment.

- *Design:* The damage is caused by a wrong design of the faulty component. In this case, the faulty parts are repaired or replaced with new ones based on a different design (update costs are not taken into account in the property damage assessment).
- *Management:* The damage is related to an improper management of the power plant, such as the use of wrong fuel or inadequate maintenance.
- *Operation:* The damage occurs during power plant operation, and it is not clearly ascribable to the categories reported above (such as a turbine blade failure, a hole in the boiler tubes and leakage currents or short circuits in electric components). Typically, such failures happen several years after the power plant erection or the device production.

3.10 Description of breakdown cause and of components reparation

In addition to the above information, further technical data are summarized in Table II. In particular, for each fault, a brief description of the event, of the breakdown cause and of the components reparation are reported.

4. Faults analysis

Overall, 23 accidents have been analyzed: 17 deals with biomass or MSW power plants and 6 deals with biogas or biofuel reciprocating engines.

The whole amount of estimated property damage is around €5,700,000, while the assessed loss of profit (only case number 10 of 23) is around €11,500,000. In 17 cases, the damage occurred after the power plant final acceptance certificate, instead, in the remaining six cases, it occurred between the provisional acceptance certificate and the final one.

4.1 Cause of loss

As shown in Figure 1, the main causes of loss are related to the power plant operation or to its erection. There is a slight difference between the subdivision based on the number of accident and on the assessed property damage.

Referring to Table I, it is interesting noting that the most of accidents related to erection/construction occurred in the first year of power plant operation (case numbers 1, 2, 4, 9, 15, 17 and 23).

Property damages of reciprocating engines fed by biogas/biofuel generally are of lower value compared to the ones of solid biomass plant due to the lower power generation capacity and, therefore, the lower plant capital cost.

In case of engines fed by landfill biogas, the main cause of loss is related to the frequent startup/shutdown cycles due to the irregular gas production.

4.2 Faulty components

The plant components that are more frequently affected are boilers (26 per cent), steam turbines (22 per cent), reciprocating engines (22 per cent) and current generators (13 per cent).

Table II. Description of breakdown cause and components reparation

Number	Event description	Cause of breakdown	Description of components reparation
Power plants fed by solid biomass and MSW			
1	Failure of several boiler superheater tubes	Improper welding	Substitution of part of tubes bundle
2	Failure of several boiler evaporator tubes	Improper welding	Substitution of part of tubes bundle
3	Short circuit in current generator (stator)	Poor electric insulation	Complete replacement of the current generator stator winding
4	Product leakage from containment basins of an HCl tank	Improper construction of concrete containment basins	Reconstruction of containment basins
5	Failure of steel structure of two cyclone filters	Excessive flue gas velocity and insufficient mechanical properties of steel	Replacement of the damaged parts of the cyclone filters
6	Deformation of main components of the biomass feeding system	Wrong design of the equipment	Substitution of damaged parts with ones based on new design
7	Damage of a steam turbine gearbox	Crack in a teeth of the low-speed wheel	Substitution of both gearbox wheels
8	Failure of several boiler superheater tubes	Excessive erosion inside the tube	Substitution of part of the tubes bundle
9	Crack in a boiler evaporator tube	Improper welding	Substitution of part of the tubes bundle
10	Short circuit in current generator (stator)	Degradation of electric insulation	Partial replacement of stator winding
11	Damage of several steam turbine blades	Foreign object damage	Reparation of damaged blades
12	Damage of many blades and shaft of a steam turbine	Bearing failure and consequent shaft deformation	Substitution of the steam turbine shaft and blades
13	Damage of several steam turbine blades	Failure of a steam turbine bucket	Reparation of damaged blades
14	Failure of flue gas duct	Excessive vibration	Flue gas duct replacement
15	Total destruction of steam turbine and current generator	Wrong turbine-generator alignment	Complete replacement of damaged components with new ones
16	Failure of refractory coating of the steam generator	Excessive thermal shock	Replacement of refractory coating
17	Damage of many steam turbine blades	Failure of a steam turbine bucket	Reparation of damaged blades
Power plants fed by biogas and liquid biofuel			
18	Failure of a medium-voltage switch (leading to reciprocating engine damages)	Improper personnel activity	Substitution of the switch (and engine reparation)
19	Failure of engine turbocharger	Failure of buckets	Substitution of turbocharger and related components
20	Failure of engine exhaust flue gas collector	Excessive thermal shock	Substitution of exhaust flue gas equipment and related components
21	Removal of inner superficial treatment of palm oil tank	Wrong superficial treatment	Reparation of the oil tank (and of engine ignition equipment)
22	Failure of engine valves and turbocharger	Excessive thermal shock	Substitution of main engine components
23	Failure of engine flue gas heat exchanger	Improper welding	Reparation of damaged tubes of heat exchanger

4.3 Power plant and faulty components age

The property damage reparation cost has been related to the power plant and to the faulty component ages. Of course the second age is more interesting than the first one because it properly represents the actual component degradation.

As shown in Figure 2 (right), the older is the faulty component, the higher is the property damage. This correlation can be explained considering that parts of older components can easily fail due to thermal and mechanical degradation and that reparation can be more difficult due to spareparts' supply.

Faulty components whose age is older the eight years caused around 67 per cent of the total property damage but only 35 per cent of the number of accidents.

In addition, as shown in Figure 3, there is no clear correlation between component age and accident rate.

4.4 Reparation time and loss of profit

As already shown, only in a few cases at the moment of the accident, there was a loss of profit insurance policy. Therefore, only in ten cases, a detailed loss of profit estimation has been carried out.

Thus, the authors related the property damage to the reparation time, which represents the period necessary to definitively repair the damaged components. In addition, this classification is more appropriate because loss of profit strongly depends on government subsidies, which are different in each country.

As shown in Figure 4 (left), the higher is the property damage, the higher is the time required to complete the reparation. It can be easily explained considering that relevant damages typically require uncommon spareparts whose supply takes a long time. In addition, disassembly/assembly operations are more complicated.

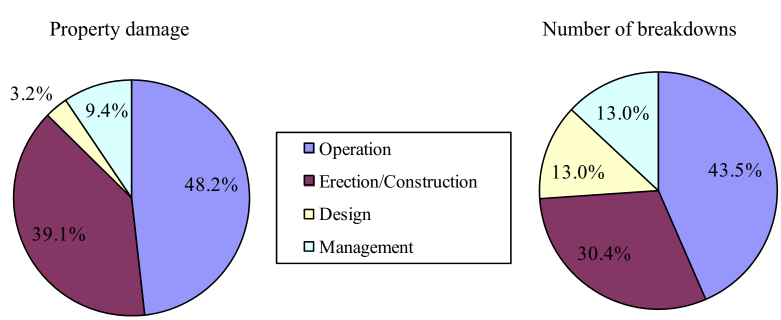

Figure 1.
Property damage and number of breakdowns divided by cause of loss

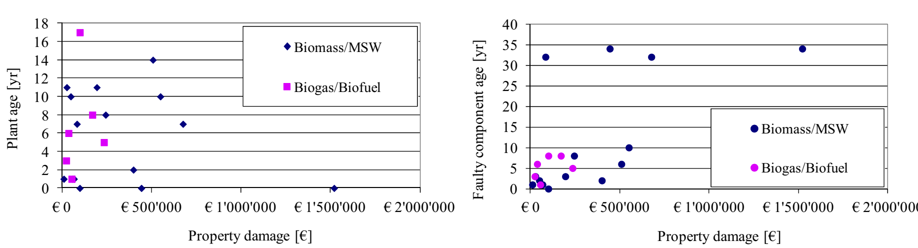

Figure 2.
Plant age (left) and faulty component age (right) versus property damage

As shown in Figure 4, also reparation of biogas power plants takes a lot of time. Anyway in the analyzed cases (landfill biogas), it does not have important effects on loss of profit because the rate of gas production varies with the age of the landfill. Therefore, in case of old power plants, the installed power capacity exceeds the actual landfill gas production. Quite obviously, this consideration is not still true in case of biogas production from anaerobic digesters.

For example, in case 18 (power plant erected in 1995), the rate of landfill gas production reduced year by year, and in the last 24 months, the electricity production decreased to half (Figure 5).

In most cases, a few years after plant erection, due to the reduced biogas production, the stop of a reciprocating engine causes a limited loss of profit (electricity and heat are generated through other available engines). Note that power plants fed by biogas from anaerobic digester are not investigated in this work.

Finally, in the ten analyzed cases with a business interruption insurance policy, the property damage and the loss of profit (plus additional variable costs) have been related: their ratio is shown in Figure 6. It should be pointed out that in landfill biogas power plants, the ratio is almost one, due to the reasons reported above (there are other available reciprocating engines).

In all the other cases, the loss of profit has been reduced through temporary reparations or rental components. This breakdown management takes a lot of time to be implemented and, therefore, only a part of the loss of profit is avoided.

In case 3 (shown in Figure 6 with a circle), two temporary reparations have been done (the first one without success).

In the ten analyzed cases, the whole loss of profit has been six times higher than the property damage.

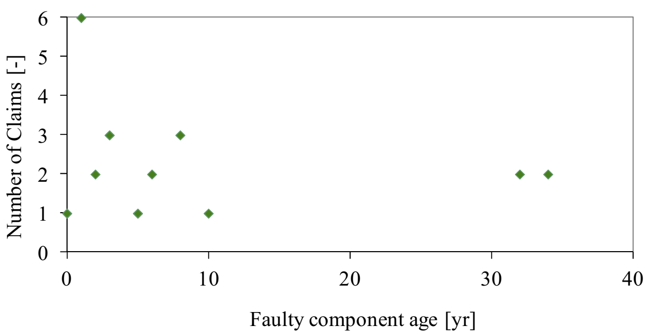

Figure 3.
Relationship between number of faults and faulty component age

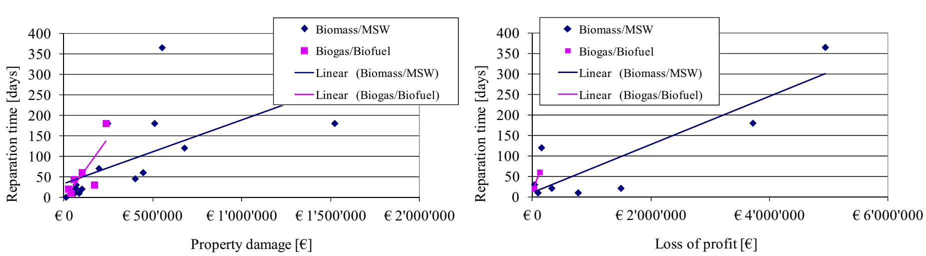

Figure 4.
Relationship between reparation time and property damage (left) or loss of profit (right)

5. Conclusions

Based on the above considerations and on authors experience in breakdowns occurred in similar plants fed by fossil fuels, the following considerations are put in evidence.

5.1 Components degradation

It should be underlined that 35 per cent of breakdowns have been caused by components whose age was equal or higher than eight, causing almost 67 per cent of the whole property damage. Even in four analyzed faults, the steam turbine was > 30 years old, when its lifetime expectancy is around 20-25 years. In many cases, the cost of reparation is higher than the value of the component at the moment of the accident. If an insurance policy exists, the energy utility risk manager and the insurance company management should properly evaluate:

Policy limitations providing deprecation of mechanical and electrical components (turbine, reciprocating engines, boilers, current elevators and generators).

Clauses that limit the insurance compensation to the value of the component at the moment of the accident (or maybe to its double).

5.2 Components redundancy

Based on the analyzed cases, the loss of profit is significantly higher than the property damage (on average, six times). This ratio is substantially higher than the one in conventional power plants fed by fossil fuels, characterized by low contribution margins and redundancy of main components.

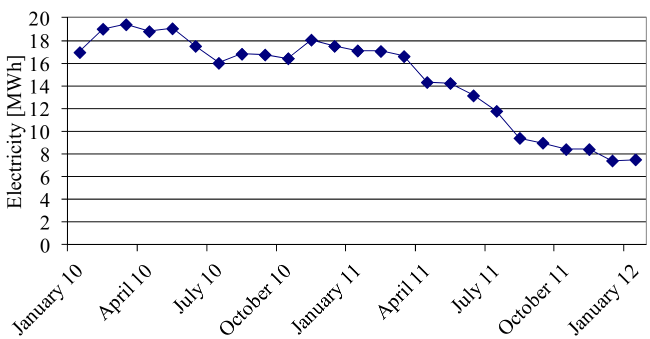

Figure 5.
Reduction of electricity generation due to lower biogas production (case 18)

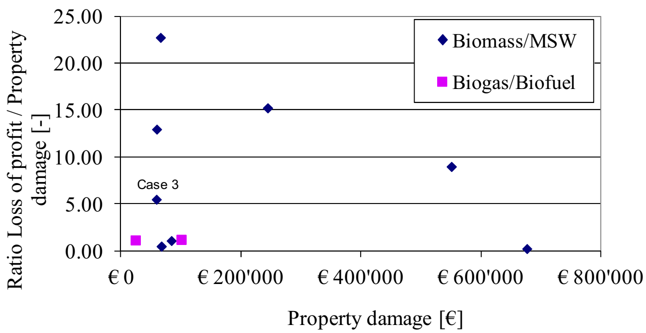

Figure 6.
Loss of profit/property damage ratio versus property damage

In addition, in the analyzed cases, the time required to complete the reparation has been higher than one month in 56 per cent of cases and higher than four months in 26 per cent of cases.

In power plants fed by solid biomass and MSW, the production stop is crucial because it is not possible to easily replace main components (steam turbine, current elevators and generators) with other available units. Energy utilities generally own and manage a limited number of power plants with different technical characteristics that do not allow redundancy of main parts.

In power plants fed by landfill biogas, the problem is less relevant because reciprocating engines are often redundant and, in case of failure of one of them, the remaining ones (that should be kept available) are able to burn all the produced biogas.

Therefore, the energy utility management should be able to provide the most critical components in a planned period of time through agreements with manufacturers or other utilities that manage similar power plants (it should be mentioned that this approach cannot be easily applied).

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