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TOOTH BY TOOTH

Do not worry, this is not a treatise on odontology nor an essay on the famous biblical statement. As our society with the toothed wheel logo celebrates its twentieth anniversary, so I thought it appropriate to write a contribution on rack and pinion railways, the more as detailed literature in English on this theme is conspicuous by its absence.

1. A short history.

Despite the fact that Switzerland is the country with world's highest density of rack railways, the principle of the toothed wheel engaging a rack bar is by no means a Swiss invention. The initial spark was given by R. Trevithick (1771-1833) who, in his erroneous belief that locomotives with smooth wheels could roll on smooth rails only if the line was laid on flat ground, equipped his first locomotive for the Merthyr Tydfil railway with grooved wheels providing the rims with sturdy nails, the heads of which gripped into longitudinal wooden sleepers. It is safe to say that the principle of assisting a locomotive with an additional device to overcome inclines, albeit primitive, had been realised. It's obvious drawbacks were the very high resistances to rolling and the rapid destruction of the wooden sleepers. To improve this design, Mr. John Blenkinsop (1783-1831), owner of a colliery near Leeds had the idea to use cast iron rails, the outside edges of which, were equipped with evenly spaced projections. He obtained a patent in 1811 and ordered from Mr. M. Murray, inventor and mechanic an engine built to his ideas. The engine consisted in essence of a boiler with convex ends and one single heating tube. On one end was the grate, on the other the chimney. The boiler was equipped with two vertical cylinders. Their pistons drove over-through rods the cranks of two axles. Both connecting shafts were mounted in the frame. Each was provided with a geared wheel which engaged another one twice as large. The axle of the latter protruded over one side of the engine bearing the main toothed wheel which engaged the above mentioned projections. The engine weighed about 5 tonnes and hauled 30 laden coal wagons. The train weight was about 94 tonnes and a gradient of 66 % (1 in 15.1) was climbed with a speed of about 5-6 km/h. Therefore the locomotive's tractive force amounted to ca. 75 kN (or about 17000lbs) and the power output was in the proximity of 120 kW (ca. 160 HP). This is a very noteworthy achievement. *(see figure 1.1)*. Although W. Blackett proved in 1814 that the friction between wheels and rails of adhesion operated engines was sufficient to overcome gradients, Blenkinsop ordered further rack locomotives

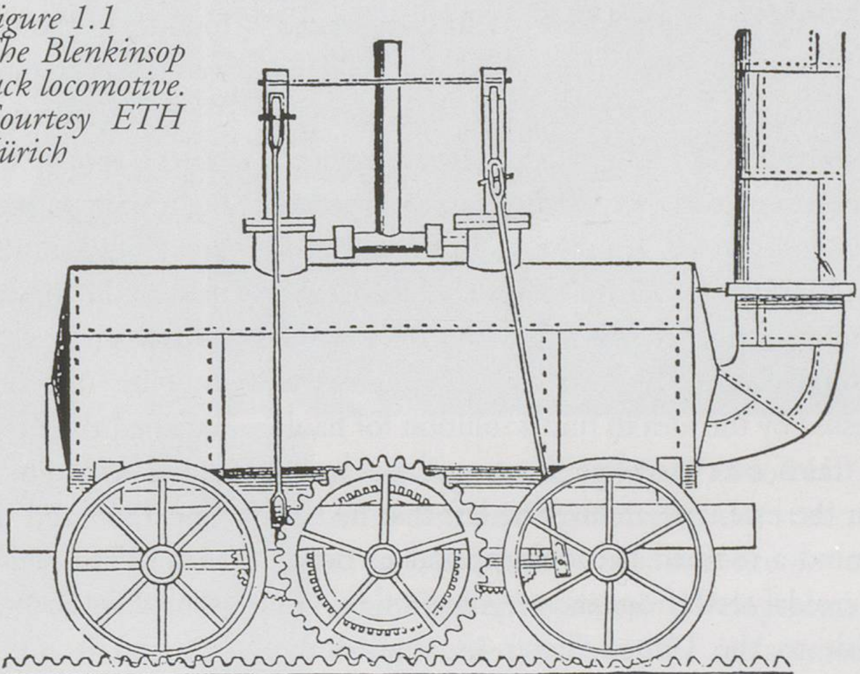
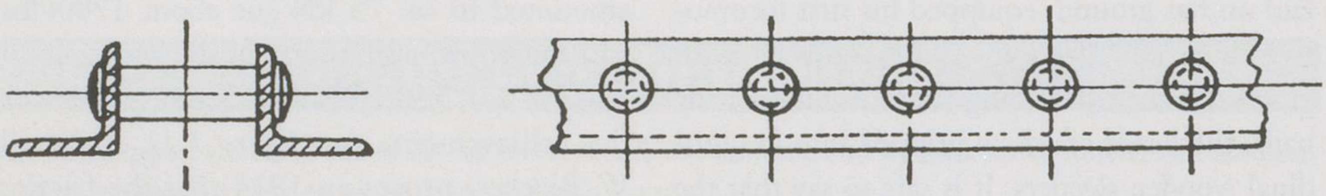


Figure 1.1 The Blenkinsop rack locomotive. Courtesy ETH Zürich

from Mr. Murray. A second important application of the rack principle occurred in 1847 on the Madison-Indianapolis Railway (USA). On this line the rack bar was placed in the centre of the track. In 1837 Herrik Aiken, father of the subsequent promoter of the Mount Washington Railway, had realised the potential of rack operations for a tourist line to the top of a mountain. But a further 28 years had to pass until Sylvester March's (1803-1884) dream of a tourist line to the 6330 feet Mount Washington became true. He was the first to use a locomotive with a vertical boiler and he invented the Marsh ladder rack consisting of two corner irons measuring 86 x 86 x 10 mm, between which round "teeth" of 36 mm diameter were riveted *(figure 1.2)*. Operation started on the 4th July 1869. With a maximum incline of 377 % (1 in 2.6) the line was soon nicknamed "railway to the moon". It is still steam operated.

As late as 1863 the first patent was granted in France to the Swiss Citizen Niklaus Riggenbach for a new rack bar design. Riggenbach (1817-1899), a gifted engineer, had acquired some experience in constructing adhesion operated locomotives in the locomotive factory of Emil Kessler, Karlsruhe (Germany) and later as superintendent of the "Central Railway" works at Olten. He was obsessed by the idea to find a solution for hauling trains over steep gradients and we know from the extensive archives he left that he had in mind a toothed bar with tapered or better trapezoidal teeth from the very beginning. On a visit to the United States he studied the Mount Washington line and he realised immediately that his patented bar would be not only safer, but also far less exposed to wear, a very important point, because the Riggenbach bar is expensive to manufacture. It may be unbelievable, but when we scrutinise lines with Riggenbach racks, we still can find sections which are more than 100 years old. At the time of his invention, the tourist industry of Switzerland was at the start of a huge expansion. Today we Swiss have a somewhat embarrassing tendency to praise ourselves for the technical achievements realised in this country.. Anybody who takes a close look at Switzerland's economic history of the 19th century will soon be aware of the significant direct or indirect influence of Great Britain caused by the stream of tourists or the gifted engineers settling in our country such as for example Charles Brown (1827-1905) founder of the Swiss Locomotive Works (SLM) or his son Charles Eugene Lancelot (1863-1924) founder of Brown, Boveri & Co., Baden. There were other important British personalities.

1.2. Marsh rack bar. Courtesy: Von Roll, Gerlafingen



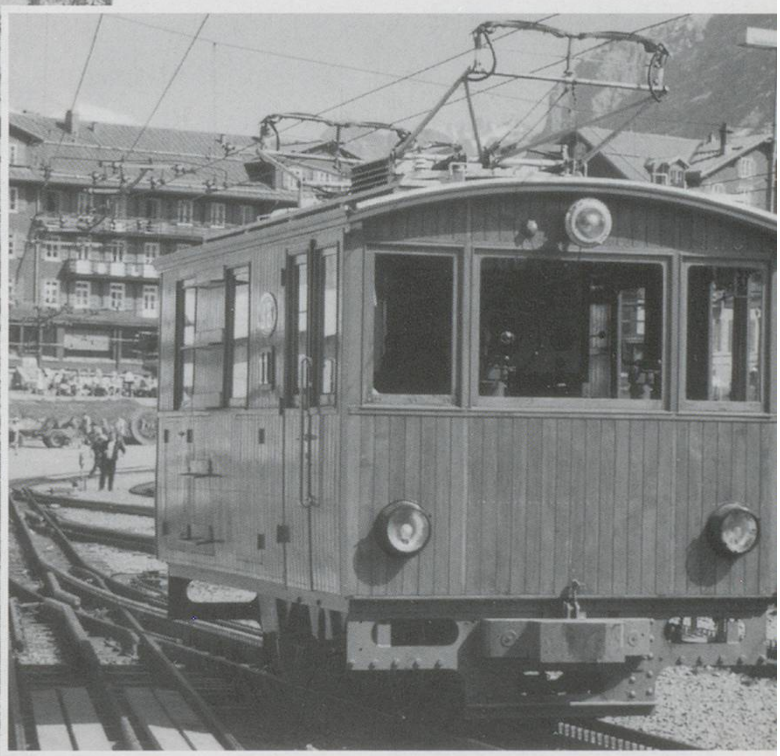
British tourists were eager to visit the hotels on the top of the Rigi mountain and pass a night there in order to admire, in the morning, the famous sunrise over the Alps. However, the road to the top was tiresome, the tourists being carried on a chaise longue, in rare cases by impolite or even rude porters. Riggenbach obtained the first concession for a rack railway from Vitznau to the Rigi mountain on the 6th June 1869 and the line opened on the 21st of May 1871 *(see illustration 1.3)*. The line was an immediate success. A rack line fever broke out in Switzerland resulting in the subsequent construction of such famous lines as the Arth-Rigi,

1.3. Vitznau Rigi Railway ca. 1872.
Photo: courtesy Central Library of Zürich

the Pilatus, the Brünig-, The Berner Oberland-, the Wengernalp-, the Jungfrau-, Brig Visp Zermatt and Furka-Oberalp lines to name but a few *(see illustrations 1.4 & 1.5)* The new system became popular in foreign countries as well because it proved to be very useful in developing the economy of mountain areas and last but not least had an enormous influence in turning a relatively impoverished population to a relatively wealthy society. This economic development encouraged in turn fascinating technical improvements such as, for example, the steam locomotives for the Austrian Erzberg line with 32 tonnes (70600 lbs) tractive force or the world's most powerful rack locomotives, the FO, VBZ and Brünig engines HGe 4/4 developing a nominal power of 1836 kW (2460 HP) *(see colour section)*. Contrary to the statements of so called experts rack lines are not obsolete. Further technical developments are being studied, such as the replacement of the rack bar and cog wheel by the linear

1.4. Brünig train ca. 1895
Photo: courtesy Central Library Luzern

1.5. Jungfrau Bahn electric loco of 1898. Summer 1984. Photo: A Hauser- Gubser



motor. In addition new lines are being discussed and the modification and modernisation of suspended lines in impoverished countries is in planning.

2. General aspects.

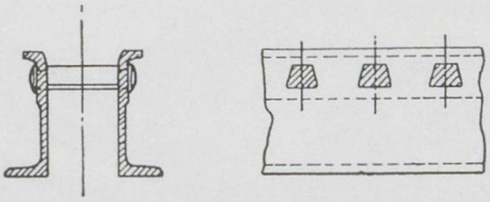
A rack line or section is used when the friction between wheels and rails (adhesion) is no longer sufficient to transmit the required tractive or braking forces to the rails. The conventional rail system is then supplemented with a rack bar placed in the centre of the track along the main longitudinal axis. Adhesion operation, albeit with very low loads, is possible up to an incline of 90-100 ‰ (1 in 11 - 1 in 10). Hence, industrial lines with their heavy loads begin rack operation on a gradient of 50-60 % (1 in 20 - 1 in 16.6). Up to 300 % (1 in 4) the vertical locking of the toothed wheel into the rack bar is still safely possible. Beyond this gradient, special systems have to be used, for example the Locher system with the lateral engagement of 2 cog wheels on the Pilatus railway.

Rack lines are either rack equipped from end to end or as a combined line with long adhesion sections and short rack operated ones. One of the advantages of rack systems is the possibility to serve entire mountain areas at the price of a relatively low investment. The operational flexibility is far higher than that of a cableway. Whereas the transport capacity of the latter is fixed, the rack line can adapt easily to the demand by running multiple units, double tracking certain sections and operating several trains on sight at the same time. One of the drawbacks is certainly the low speeds in rack sections, but this is of a lower importance than on main lines where the automobile or truck is a dangerous competitor.

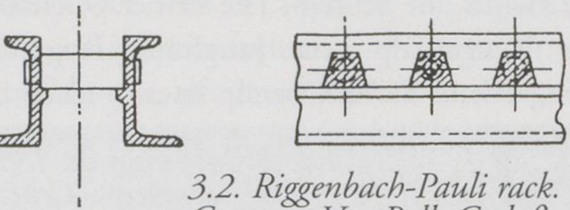
3.Rack and Track.

The Riggenbach rack is a very solid bar withstanding high tooth pressures if correctly mounted, consisting of two angled irons in which the trapezoidal teeth are riveted. The

3.1. Riggenbach rack bar.
Courtesy: Von Roll, Gerlafingen



dimensions vary, depending on the tooth pressures, but as far as possible Riggenbach stuck to a pitch of 100 mm helping in the economical production of the bar. Maintenance is low. One of its drawbacks is the need for higher radius curves than with other systems. *(see diagram 3.1)*

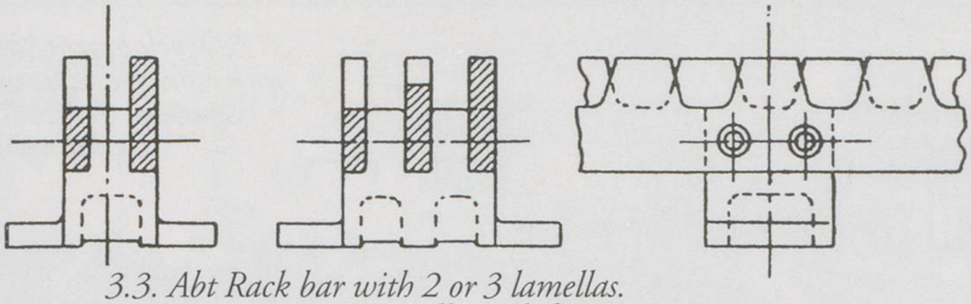


3.2. Riggenbach-Pauli rack.
Courtesy: Von Roll, Gerlafingen

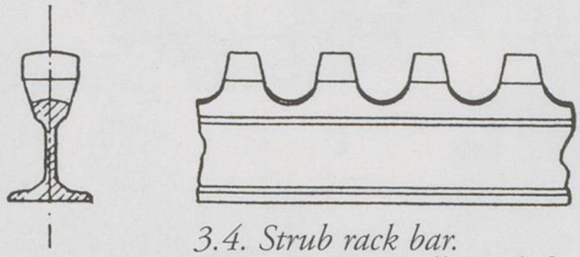
Mr Pauli, an engineer of the Maschinenfabrik Bern, modified the Riggenbach rack by using profiles of rolled steel with a reinforced upper half. This type is lighter, but sustains the same tooth pressures. *(see diagram 3.2)*. One of the lines equipped with this type is the Wengernalpbahn.

Roman Abt (1850-1933) invented the lamella rack named after him. It consists mainly of two or even three rows of steel teeth machined out of a solid bar and placed vertically in the centre of the track. The teeth are staggered in pitch. Hence the toothed wheels of the engines have to or three rows of teeth. This type is relatively light, easy to mount, but is difficult to clean snow and ice from. It is widely used on lines with combined rack and adhesion operation *(diagram 3.3)*

Another type was invented by Viktor Strub (1858-1909). It is made in essence out of a special rail profile. The teeth are milled out of the relatively wide rail head. The manufacturing is expensive but it is easy to mount and to maintain. It is widely in use on lines with rack from end to end.*(diagram 3.4)*.



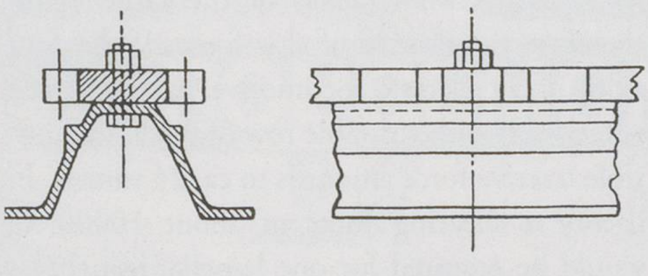
3.3. Abt Rack bar with 2 or 3 lamellas.
Courtesy: Von Roll, Gerlafingen



3.4. Strub rack bar.
Courtesy: Von Roll, Gerlafingen

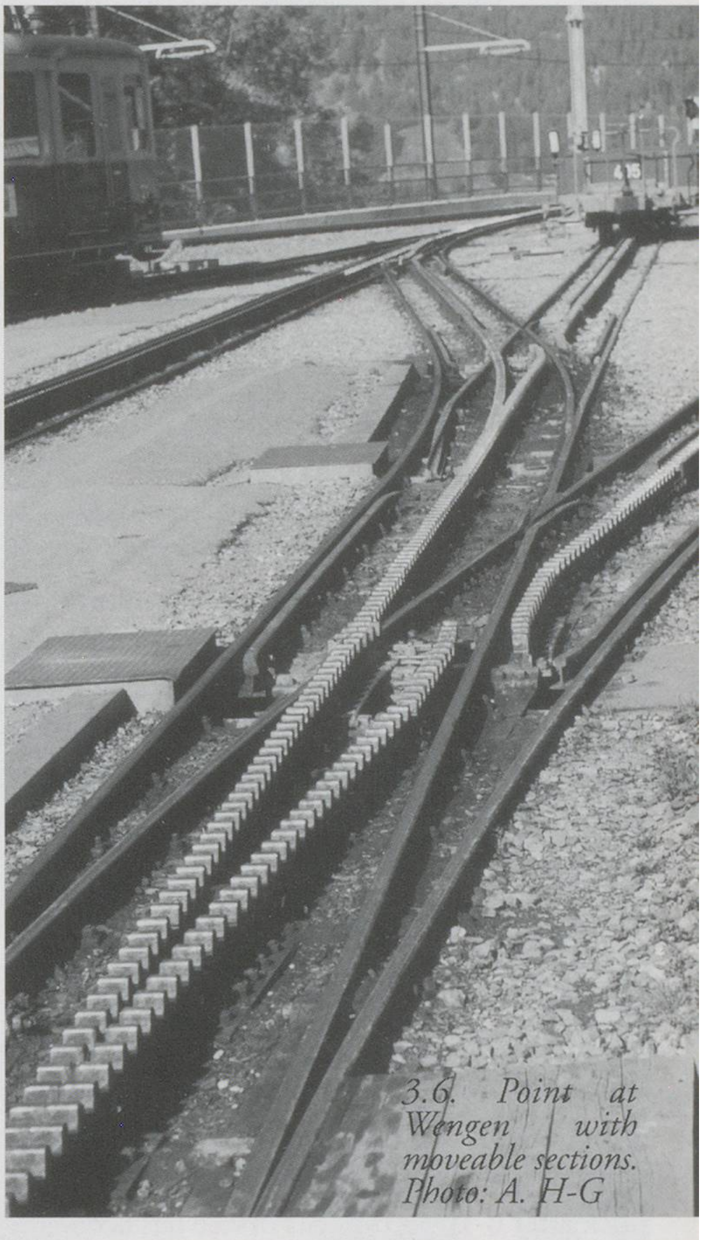
Eduard Locher (1840-1910) invented the Locher bar which he provided with two parallel sets of horizontal teeth. Each axle of the engine is furnished with double horizontal pinion wheels driven by vertical shafts. These lock into the central rack from both sides. The Pilatus line is equipped with this type which has proved to be the perfect solution for the incline of 480 % (c. 1 in 2) *(See also diagram 3.5)*

3.5. Locher rack bar.
Courtesy: Von Roll, Gerlafingen



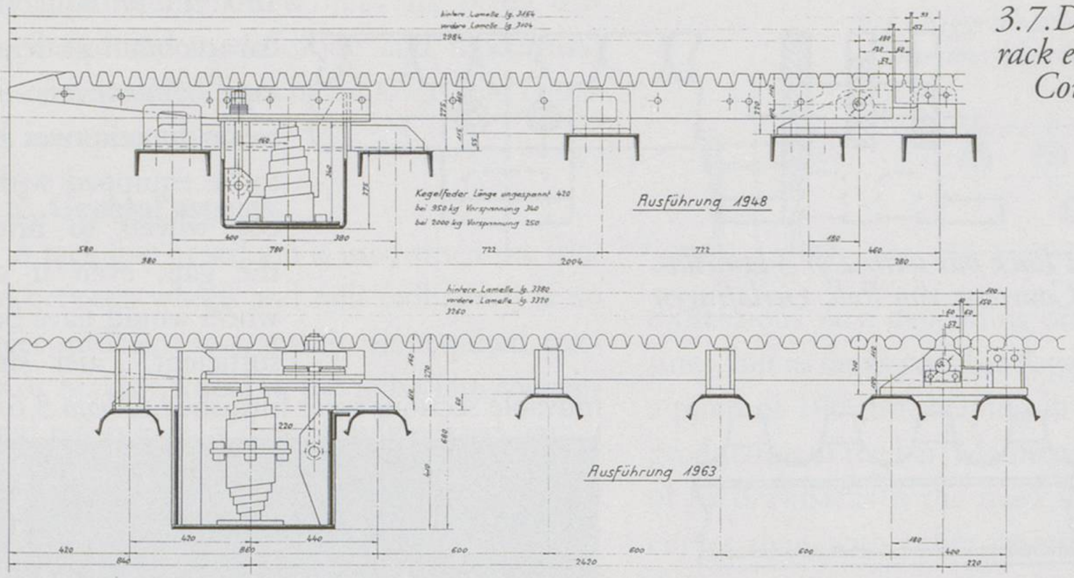
Modern lines are provided with the Von Roll rack which is an improved lamella rack, very sturdy, made for high tooth pressures, easy to manufacture and to lay. In principle it is one lamella of the Abt rack, but heavier and of greater width.

The management of rack lines usually shun points like the devil. They are expensive and hard to maintain. The Furka-Oberalp has 3 (!) points in rack sections. On the very first points in use there was always a section of about 90 - 100 cm without rack bar to obtain a safe passage. However, the steam locomotives had to be equipped with 2 cog wheels to bridge the gap, even if one wheel would have been sufficient. Later small movable sections were furnished. *(Photo 3.6)*

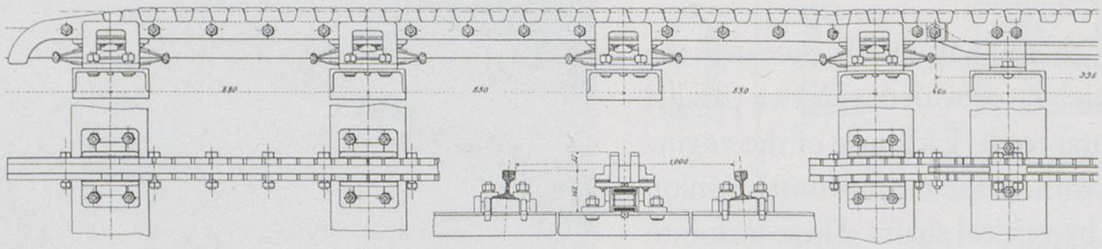


3.6. Point at Wengen with moveable sections. Photo: A. H-G

A critical moment for the engineer and his engine is the moment of entering a rack section. *(illustration 3.7)* The possibility of the engine climbing onto the teeth has to be avoided in any circumstances. Lines first started with a speed reduction to 2-3 km to avoid damages or derailments. Then a quite satisfactory solu-



3.7. Development of rack entrance sections. Courtesy: Von Roll, Gerlafingen



tion was found by adapting the revolutions of the cog wheel to those of the driving wheels. Special devices were invented to inform the engineer when this had happened. Although far better than the first solution, damage to the pinion wheel and the rack bar were quite frequent due to the rigid installation of the entrance section. A team of SLM engineers developed a separate rack section which was connected by springs to the normal bar. At the front end this section was mounted on strong springs which had to support the tooth pressure. A clever device forces the pinion wheel to turn at a lower speed than the driving wheels. Due to the pressure and the draw on the entrance section, the pinion wheel falls into lock after 6-10 teeth. This device has been continually improved and allows today entering speeds between 10 and 20 km/h.

An important point to be considered when constructing a new locomotive is the tooth pressure dictated by the bar systems. The forces which can be applied depend obviously on the size of the teeth, but the fixing of the bars is at least as important. As a rule of thumb a shearing force for the fixed bar of about three times the force on the tooth has to be sustained. On an Abt lamella, about 100 kg tooth pressure can be sustained per mm width. A lamella of 30 mm width withstands therefore about 3000 kg (6613 lbs), two lamellas of the same width therefore the double of this force. If the four axles of an electric locomotive have one cog wheel each with a double row of teeth, the possible tractive force amounts to ca. 24 tonnes. In theory a shearing force of about 10000 kg would be required for one lamella, but this is rarely possible due to the prevailing geological conditions. The locomotive designer is well advised to clarify first the conditions on site before looking at the drawing board. On the other hand Riggenbach bars have been built for a tractive force of 18 tonnes per rack and pinion wheel operating perfectly well. Other systems withstand similar forces.

In the next instalment we will discuss the most important locomotive designs.

WHAT YOU MISSED AT THE AGM

1. Dave Howsam brings the meeting to order. **2**. General view of the meeting. **3**. Contikits Geoff together with Alison, Dave & Ernie(NIP). **4**. Daniel Davis and Disieux, his captivating Z layout with it's exquisite detail. **5**. Ian Edwards and Keine Name. **6**. Gerry Savine, whose superb prints taken from his own paintings are becoming collectors items. **7**. Sean Healey and his N gauge layout, Kleine Schweiz. **8**. Roy Pakeman and his breathtaking interpretation of Rougemont on the MOB. **9**. The ever cheerful Sue and Chris from MITV