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5 - Fundamental Principles of Steam Locomotive Modernization and Their Application to Museum And Tourist Railway Locomotives

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Abstract: Modernization is the partial applicaton of technological advances to existing locomotives without the introduction of structural changes. The basis for this is that **it is false that the steam locomotive reached a pinnacle imposed by its very nature**: CHAPELON was the first to work along this guideline from 1926 onwards, and the author, his disciple, continued the work. Whilst a number of mechanical developments, most of them of American inspiration, need to be recorded, **thermodynamic advances make up the bulk of the progress**. Increased power, better fuel economy, compliance with environmental laws etc. may lead to modernization demands for tourist railways. Museum locomotives are also capable of justifying modernization on the grounds that they should show the development of the technology by exhibiting not dead fossils but live, moving engines. And modernization certainly is a real live show because it offers to the public and the student the locomotive in motion. For modernization is motion, real live motion indeed!

1 Introduction

Steam locomotive modernization is the application of principles fully adopted in advanced locomotive design to existing old engines, without involving structural changes, and for the purpose of improving their performance. This is not new, and its fundamental ingredient is advanced applied thermodynamics, not replacing spoked by BOXPOK wheels, fitting a superheater throttle or thermic syphons. The real initiator of this technology was CHAPELON in about 1926. The author started to put it into practice in 1952, and is still continuing to do so today: it is a "commercial" development. The possibilty of applying the fundamental principles for a different purpose, namely tourist and museum railways, is an unexpected field. Obviously, the first thing to do is to explain to the concerned authorities what modernization means, so that they can determine whether they can get benefits from this technology: this is the aim of the present paper because unfortunately there is a serious lack of well-distributed information on steam locomotive matters. Most of

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what will be said in this paper will sound repetitive to professional ears. But here we are, and the point is to convey a message the first statement of which is:

It is not true that the steam locomotive reached the pinnacle of its development.

Most steam locomotive engineers do not believe this statement. The main reason behind this is the fact that CHAPELON wrote in French, not to mention the self-satisfaction that characterized many of those involved in steam locomotive development in the past.

Enhanced locomotive performance for "commercial" railways can be justified by a number of reasons, such as increased line capacity, the substitution of coal or alternative fuels for oil, the avoidance of costly investments in diesel locomotives, and, nowadays, compliance with pollution laws. For tourist and museum purposes, the reasons are certainly widely different, and the author leaves this subject, as stated above, to the authorities concerned: the scope here will be limited to a description of what modernization means so that they can understand it and reach their own conclusions about it.

2 What is modernization?

By 1920, the steam locomotive had to withstand the challenge of railway electrification. The fundamental argument for electrification was an increased thermal efficiency leading to a definite reduction in coal consumption. One should not forget that at that time coal was mostly laboured by hand, which was very expensive (except in Britain), while the hardest services required premium fuel: low ash, no clinkers, good size, good coking properties etc. The answer was mostly sought by developing those unconventional locomotives admirably described in STOFFEL's book [10]. However, the results obtained so far with non-STEPHENSONian locomotives were never convincing although some sixty different designs were tried out, including a number of turbine, uniflow etc. machines – in some cases these engines were utter failures! ANDRÉ CHAPELON was the engineer clever enough to realize that the answer was not to be sought in exotic designs, but in eliminating from the STEPHENSONian scheme a number of **absurd** imperfections, perhaps the most significant of which was a poor internal streamlining and flagrant violations of thermodynamic fundamentals. He discovered this when, after sweating to keep 16 atm boiler pressure firing PLM locomotives, his drivers destroyed his painful efforts by throttling ("strangling" one should say) the pressure down to 10 atm at the cylinders. His drivers? No. The **mechanical engineers** were responsible! Curiously, the latest and best locomotives suffered most: the French compounds!

A steam locomotive can be thought of as a simple machine: there are the cylinders in which the pistons receive the action of the steam pressure with expansive working, of course, for fuel economy: there are no reasons for waste. There is a boiler whose duty is to provide the steam needed to feed the cylinders. What determines the maximum power? Given that the boiler is large and efficient enough, the size of the cylinders, of course. Enough adhesion weight is to be provided to avoid slipping. If high speeds are sought, then tall wheels are essential (think of the 2,3 m of the DRG 05). And that is all. That has been the very basis of locomotive design in the USA, England, India, South Africa etc. Development was achieved by trial and error, on a merely empirical basis. Exceedingly good performances were realized: in 1895, the British covered the 869 km between London and Aberdeen in 8 h 29 min with three stops, in the middle of foggy nights!

There is another concept of the steam locomotive:

The steam locomotive is a machine the purpose of which it is to transform the fuel chemical energy into mechanical work at the drawbar.

This **thermodynamic** concept of the steam engine became firmly established by CHAPELON in 1926. But since he wrote in French, the world outside France ignored it. The last of the British steam locomotive giants, BULLEID, said that "thermodynamics never sold a single locomotive" [11].

10. Stoffels, W.: Lokomotivbau und Dampftechnik. Birkhäuser-Verlag, Basel und Stuttgart, 1976.
11. Click, J.: Personal communication, 1977.

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Thermodynamics makes a different approach. There are two fundamental equations for the steam locomotive:

$$\text{Power [kW]} = \frac{\text{Steam produced by the boiler [kg/h]}}{\text{Specific steam consumption [kg/kWh]}}$$

$$\text{Power [kW]} = \text{heat input [MJ/s] x thermal efficiency [\%] x 10}$$

Thus the power is limited by the boiler, while the function of the cylinders is to extract the maximum work from the steam supplied. It is irrelevant to have large cylinders if they are inefficient. The second equation shows that the limit is determined by the ability of the boiler to burn as much fuel per hour as possible, but the resulting power is determined by the thermal efficiency. Both thermodynamic equations, which many steam engineers will now see for the first time in their lives, are of course of academic nature. But **CHAPELON proved, by means of the performance of his unequalled engines, that they are at the very heart of any steam locomotive**, whether it is the best or the most mediocre one. This understanding is essential in order to grasp the nature of the modernization.

The thermodynamic nature of the steam locomotive calls for a minimization of what are called **irreversible losses**. An example of these are pressure drops that do not produce work, as in the case of CHAPELON's driver: reducing, by throttling, the steam pressure of 16 atm at the boiler to 10 atm at the cylinder inlet is an irreversible loss. Thus modernization requires an improvement of all steam passages to minimize ineffective pressure losses: this is called improved **internal streamlining**. On a classical steam locomotive, when it is forced to develop greater power, the specific steam consumption tends to increase sharply. At a certain point, maximum power is obtained because the breathing capacity of the steam circuit (pipes, valves, exhaust nozzle etc.) is exhausted: this is what the Americans call "capacity power". If the same engine is provided with larger steam passages, large valves, improved draught ejector etc., the specific consumption also shows an increase, but the limit is beyond the capacity of the boiler to supply steam: the power of the locomotive is defined by the boiler.[12] CHAPELON was the first to demonstrate this fact, although it was expressed in a different form by MALLET. For different speeds, a different set of curves is obtained. The English-speaking world did not even suspect this interpretation of locomotive phenomenae.

As the various steam passages are not infinitely large, for a given cut-off the speed-tractive effort line drops. For a poorly designed engine, the lines drop so much that the breathing capacity is exhausted: no matter what the ability of the boiler to supply steam may be, there is a maximum power which cannot be surpassed. If good internal steamlining is provided, this breathing capacity is so large that the limit is outside the interesting operating range, i.e. beyond the evaporative capacity of the boiler (see CHAPELON [[13]]).

There are a number of other losses which are now not only identified, but quantified, while at the same time means are provided on the hardware to reduce them to a minimum (piston ring leakage, incomplete combustion, wall effects in the cylinders etc.).

A most important thermodynamic concept is that of the ideal engine: this is the one in which, for given steam conditions, all phenomenae occur without irreversible losses (for example, no piston ring leakage, no radiation etc.).

The production of draught as demanded for combustion and heat transfer in the boiler requires an energy which, in the form of back pressure on the pistons, reduces the otherwise available power. This obeys the ROSAK-VÉRON dictum (as complemented by the author):

> **The design of a combustion and heat transfer apparatus is a compromise between its bulk and the cost of energy required to circulate the fluids** [[14]].

12. In the usual operating range (for example below an evaporation rate of 57 kg/m2h), the difference is not particularly great.
13. Chapelon, A.: La locomotive à vapeur. Baillières et Fils, Paris, 1938.
14. Rosak, C. and Véron, M.: Nouvelles études sur la chaleur. Paris, 1935.

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This principle was (and still is!) unknown to steam engineers – but not to the locomotives themselves!

Thus, the boiler cannot be indefinetely forced by sharpening the blast. With ordinary ejectors, this corresponds to a smokebox vacuum of appr. 150 mm H_2O. CHAPELON, ca. 1930, developed the KYLCHAP ejector leading to vacuums of 300 mm H_2O and more, thus obtaining greater evaporations, say 100 kg/m^{2}h, with acceptable back pressures. Associated with a better internal streamlining, the actual power developed at the drawbar was in some cases doubled in the higher speed range. The author's LEMPOR increased that figure to 140 kg/m^{2}h.

CHAPELON started his work not by building new locomotives, but by modernizing existing ones. A summary of his main principles, all showing a multiplicative effect between themselves, is as follows:

- improved thermodynamic cycle: higher steam pressures and temperatures, feed water heating etc.;
- increased power-to-weight ratio due to the improved thermodynamic cycle, the KYLCHAP ejector (lower back pressure!) and the heavily improved internal streamlining;
- elimination of the well-known defects of compound locomotives, especially in high speed services (these defects were mainly due to the poor internal streamlining of pre-CHAPELON locomotives);
- great efforts to make each part of the locomotive approach the theoretical ideal so that the efficiency of the real engine as a whole comes close to that of the ideal machine;
- as a consequence of these measures, the fuel consumption per unit of traffic pulled was considerably reduced.

The author contributed to the above scheme by:

- the GPCS (Gas Producer Combustion System), which allows a further increase in boiler evaporation and the virtual suppression of solid emissions and smoke;
- an improved general theory;
- even higher steam temperatures;
- air preheating by exhaust steam;
- mechanical improvements;
- advanced, heavy duty feed water treatment;
- "exaggerated" cylinder insulation etc.

3 Application of principles

Even some basic alterations may produce the spectacular results shown in Fig. 1. All this depends on the possibilities afforded by the existing design and the particular aims of the owners, and of course on the available money.

What follows may be considered as a project of maxima, for example, as the one studied by the author for the Chinese QJ 2-10-2 so as to reach a power of 5,500 hp (diesel equivalent).

- the boiler pressure is increased as much as possible whilst complying with the corresponding boiler code. A fundamental concept is that, except for the firebox, **steel does not age**. With TIA type water treatment, no corrosion occurs;
- the steam temperature is increased up to 450°C;
- an investigation is carried out concerning all important or **minor** defects so as to correct them (usually between 20 and 100!);

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- the GPCS is arranged so as to comply with environmental laws, particularly concerning CO-, NO_x- and solid emissions;
- improved piston valves with minor alterations to the valve gear;
- improved lubrication throughout, both for the cylinders and the machinery; length of run without nursing appr. 2000 km;
- "exaggerated" cylinder block insulation;
- feed water and air preheating by exhaust steam to appr. 135°C (and also by receiver steam);
- use of the whole tender as hot water reservoir;
- automatic air-tight dampers;
- advanced cylinder tribology;
- improved ergonomy both for driving and maintenance;
- reviewed balancing and track forces;

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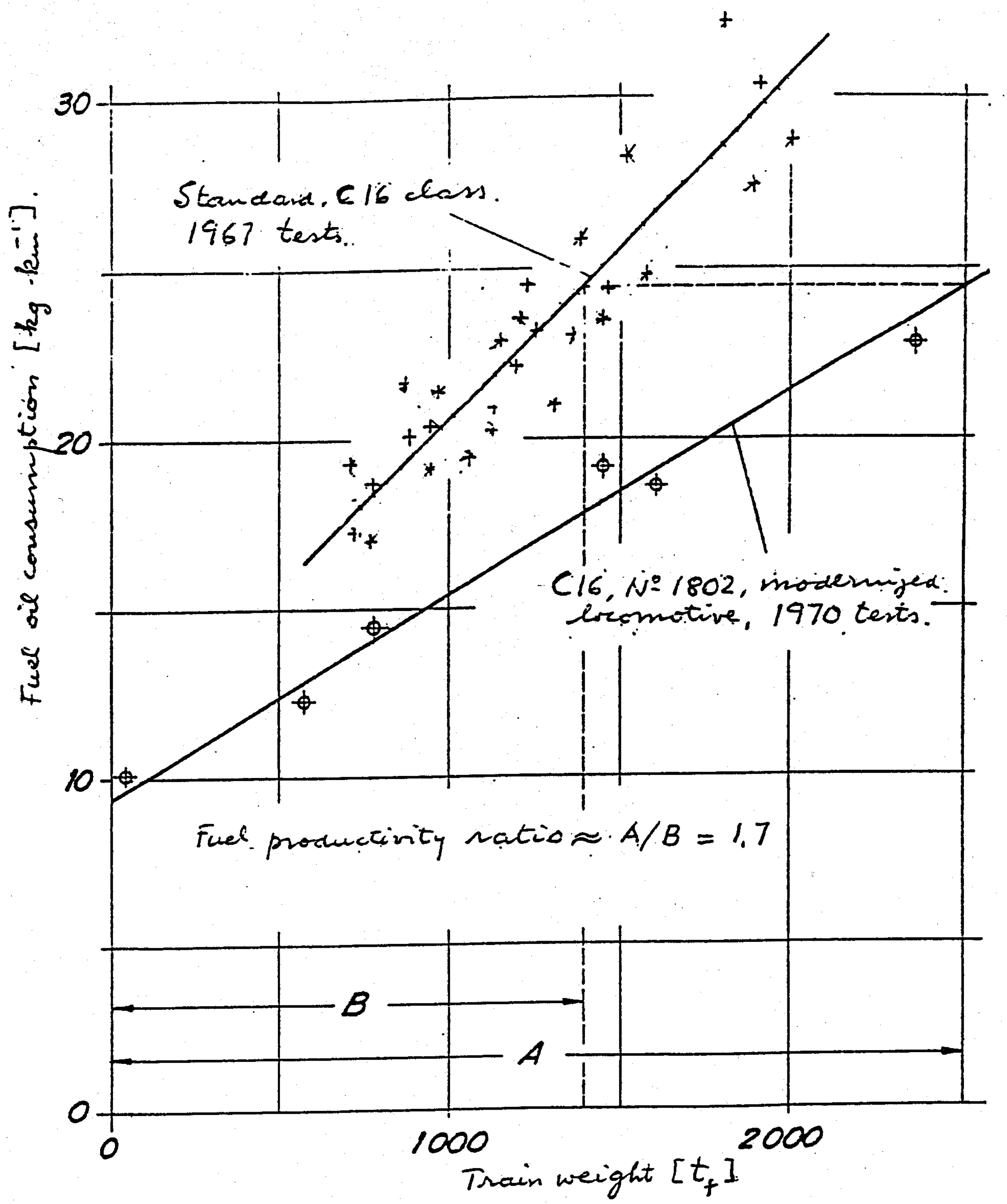

Fig. 1: Effect of a slight modernization on fuel productivity.

FCGB, Argentina. Non-stop freight trains, flat level lines, Chaco area. Standby fuel not included. It is seen that the fuel productivity is increased by appr. 70 % because with a given consumption a heavier train is pulled.

- improved boiler insulation;
- economizer;
- general mechanical improvements;

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- light-weight reciprocating parts;
- substitution of the uneconomical turbogenerator;
- advanced feed water treatment eliminating corrosion, scale, caustic embrittlement and giving pure, uncontaminated steam;
- in certain cases one man operation;
- **POISSONNIER repair methods**;
- new cylinders of advanced design;
- three cylinder compounding according to the author's scheme;
- improved, duplicate, pedal operated sanders;
- anti-slipping devices etc.

The above list should be completed by a number of details and alternatives, totalling perhaps 500, as an answer to minor problems which may become determinant of the performance:

No horse will run faster than what is the limit of a poorly fitted horseshoe spike.

So far, the whole question has been looked at from the standpoint of "commercial" railway operation. However, this point of view may also hold true for tourist traffic as, for example, on the Grand Canyon Railway, USA.

4 Steam locomotive modernization for tourist railways

The author is not conversant with the tourist railway business. However, a representative opinion poll in Austria revealed that 79 % of the passengers prefer a steam train: there is some unexplainable difference! So if the decision has been made in favour of steam, the requirements may be various:

- increased power;
- improved performance;
- reduction of operating costs;
- compliance with environmental regulations;
- others.

Increased power may be imposed by running under catenaries so as to avoid traffic disturbances. This may be associated with the need to avoid the deterioration of such performance along the kilometrage after the last overhaul. Or it may be demanded by the ever increasing traffic invariably experienced by tourist **steam** railways. Improved performance may take the form of a perfect reliability: a hot big end is for sure a tragedy.

The reduction of operating costs should not be discussed. Business profits result from the difference between income and expenditure. Longer, reliable runs are more economical; this should always be aimed at. One-man operation is an attractive proposal.

Sooner or later, smoke will be banned by the environmentalists. The GPCS, as proven in practice, makes a perfectly transparent exhaust possible. CO-, HC-, and solid emissions are extremely low, NO_x-emissions are very close to or at the theoretical minimum. It should not be difficult to obtain coal at promotion prices from coal syndicates. Of course, no clinkering is to be accepted, but the GPCS can control it. Alternatively, cheaper clinkering coals can be used.

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5 Modernization of museum locomotives

The function of museums may be extended not only to preservation, but also to a live preservation of the various railway vehicles, i.e. they should not be shown as static exhibits (i.e. dead) but in motion: this already happens in certain countries. In the case of steam locomotives, a number of problems may arise, ranging from hot boxes to the most frequent ones: indifferent steaming, boiler scaling and foaming. The appropiate technology to solve these problems is nowadays available.

A philosophical question comes to the fore: all preserved locomotives have suffered many changes along their lives, of which perhaps the most frequent one was fitting a superheater. What should be the state selected for preservation? The last one? Has that process ended? A steam locomotive is more than the cold hardware: it is a live being; all the alterations introduced along its life are the proof of this. In fact, it **is** a modernization process. Fig. 2 shows an Argentine locomotive built in 1888 the valve gear of which was altered by the author in order to improve her performance. This was necessary because of cars added to the historical train which she pulled. Retrofitting the GPCS is now being considered to avoid the sparks resulting from wood firing. To appease pure preservationists, No. 10, a sister engine, has also been put in service in its original condition as 0-6-0. The moral is that each museum should offer the general public and locomotive students an example of a full modernization showing that the steam locomotive is far from being dead: this is more important than putting fossils on exhibition!

6 Concluding remarks and recommendation

The steam locomotive is far from being a simple machine. It is very complicated, but its complication is of an intellectual nature. In the past every railway had to have an engineering office; nowadays this painful task has been transferred, in the case of diesels, to the manufacturer. This happens with all technologies, from airplanes to shoes. Running tourist railways and museum trains is a matter for professionals, and even in this case, they, unlike their predecessors on state or privately owned railways in the past, lack the institutional support which was developed over more than a century. Much of that institutional support has been lost, and enthusiasm and willingness is not enough to solve the problems.

It is false that the steam locomotive reached the pinnacle of its development potential.

As a matter of course, steam engineers who are still alive will not accept that: they prefer an honorable defeat by the diesel, although not to the extent that the the author once heard: "We have thrown steam into a ditch, and it is better for you to leave it there!" They look upon modernization with horror because it is change that they did not generate themselves. The author believes to have generated much change and advancement. Some of the old important engineers of the steam locomotive, now dead, supported him, like CHAPELON, who after a lot of angry discussions accepted, for example, the GPCS; some others (E. S. COX) described it as "abortive". The reader who is faced with the need to increase the power, reduce the fuel bill, abide by pollution laws etc. has to judge for himself whether modernization proposals are reasonable or merely fanciful. He should, however, remember the fact that:

He who knows how to paint does the painting, not he who wants to.

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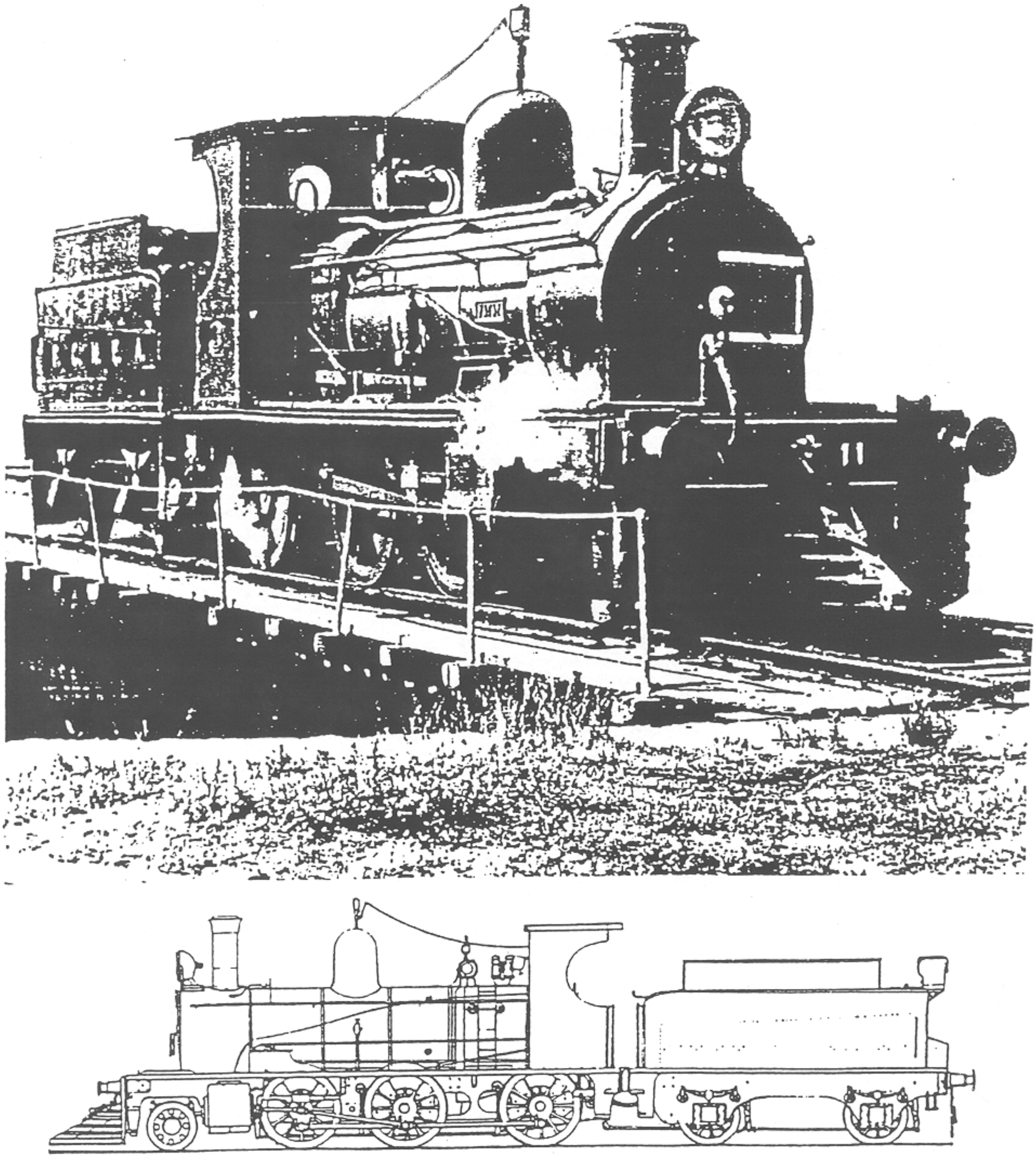

Fig. 2: NEILSON No. 11 (built in 1888), FCGU, Argentina.
Modernized by the author in 1991.

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