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Lectures on Steam Locomotive Operation in the 21st Century

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Lectures on Steam Locomotive Operation in the 21st Century

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1 - XXIst Century Steam

Jornada de la tracción de vapor moderna

Day of Modern Steam Traction

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Buenos Aires, Dec. 15, 1997.

Contents

Abstract: It is **false** that the STEPHENSONian steam locomotive attained the maximum possible degree of thermal efficiency, performance, productivity, and financial return on investment. This is a widespread opinion shared by steam engineers who, after the war, did not produce advances in parallel with other technologies. The author has kept to the STEPHENSONian configuration, albeit introducing a number of mechanical improvements largely of American inspiration. Three important developments have been made:

– advanced **thermodynamics** for drastically increased fuel efficiency,

– **biomass** as a non-polluting, regenerative fuel and

– "heavy duty" **feed water treatment**.

The proposed technology will be the most recent to be developed in the First World. Yet it must fit Third World requirements because diminishing natural resources (esp. oil) and pollution will be **global** problems in the 21st century [1].

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1. For a much fuller discussion than can be given in this paper, see the author's forthcoming book: Porta, L. D.: Advanced steam locomotive engineering facing the energy crisis.

1 Introduction

All over the world there is a steam renaissance. Whilst this is at present limited to tourist trains, new generations are beginning to realise that steam can be used to run trains in a manner far different from the one often portrayed by the media. There are a number of reasons for this new attitude, as will be discussed in this paper. The present is an era of admirable "super-technologies" (which also include "super-expectancies"). There are however problems which these super-technologies cannot meet, and these may be decisive. Steam enthusiasts will be delighted to hear what follows in this paper. However, they **must** realize from the very beginning that the advent of XXIst Century Steam is not a comeback of the steam locomotives which they once loved. Instead it incorporates the most advanced level of modern engineering, even if the wheels are still round, the boiler is still used to evaporate water and a bunker is still used to carry the fuel.

The title of this paper could be misleading: it should have read "the author's steam". It is not the intention here to discuss future steam traction in general, with all its possible variants, but simply to present **his** approach to the problem. This may be a pedantic attitude but, so far, he believes that there is merit in doing so. One day, if what follows in this paper is converted into a sound business, that attitude will be considered irrelevant: what will count is the essence of the proposal.

The steam locomotive proposals presented here do not refer to "super" transportation duties, super speeds, super tonnages, super traffic intensities etc. but rather to the more humble duties which make up everyday life for the majority of people. This does not mean that high speeds or heavy tonnages lie beyond the range of services: remember that 5,000 t coal trains were at one time considered for the Rio Turbio Railway, Argentina, 750 mm gauge, 30 kg/m rail. Millions of passengers will be happy if they can travel in a decent manner rather than on the roofs of the coaches!

2 The Background

The First World is saturated: everybody has a house, medicine, transport, motor cars, education, theatres, holidays, spare time etc. Production costs are constantly decreasing. Money (i.e. effort) which was at one time allocated to the arms race is now available for any use, but this use is no longer to be found in the First World. Therefore, if the process is to continue at the same momentum, a new market (in the broadest sense) is to be found: this is the Third World. An immense market! That World wants to become a consumer society, yet it must be taught how to consume, and its immense richness needs to be developed for useful purposes. Thus, the First World will take its tremendous potential of know-how and capital to the Third World, as is already happening. This will in turn lead to a huge industrial and trade explosion, in turn necessitating a transport explosion. This explosion cannot, by force, be a road transport explosion. A **railway** one is what is required. The question does however remain: **which form of motive power is to be used?**

Parallel to the above, **pollution** will develop exponentially. Whilst noxious gases resulting from the imperfect combustion of hydrocarbons are already creating a great deal of anxiety, the greenhouse effect, caused by CO_2-emissions, is perhaps overwhelming. What can be done to prevent this problem? Advanced, XXIst Century Steam can, as will be demonstrated, provide the answer by running trains on biomass fuels, i.e. on solar energy.

This answer must however be developed by the First World, as the Third World will not use locomotives if they are not considered to be of the latest technology. The engines proposed in this paper will certainly reflect the latest technology, as they do not harm the environment, do not use oil and are cheap to build and maintain. Furthermore, the First World should also start to use them, otherwise it will be suffocated by contaminants produced by road traffic and the other forms of motive power.

3 General Considerations

The development of steam traction may be divided into four generations of locomotives:

– Generation "zero", the bulk of which was built around 1920, which now probably makes up between 60 and 70% of the world's existing stock still in operation;

– First Generation, the most recently built steam locomotives: the NIAGARA, the South African 25 and 25 NC, the post-war British and German standard locomotives, the 141 P, 141 R, the BIG BOY etc.;

– Second Generation, the locomotives which it is possible to build today, incorporating the technological advances from 1950 to date;

– Third Generation, yet-to-be developed engines, the prototypes of which would cost US \$ 10^9 to develop and build.

What follows in this paper refers to the Second Generation locomotives as an immediate answer to the challenges faced today. The author adheres to the classical, STEPHENSONian scheme. It does not hold true that, as many people (including steam engineers) believed, it reached the pinnacle of its potential development. This is a point first put forward by CHAPELON in 1926. CHAPELON had discovered that the way to progress was not through the fancy schemes then being proposed as a means of facing the challenge of electrification, but rather through the correction of a number of engineering imperfections which were accepted as natural at the time. Of these imperfections, the lack of sufficient internal streamlining was perhaps the most important. This of course was not (and is not) the sole step to improvement; the author has advanced along the same line of thought according to the following incomplete summary:

– cycle improvements: 20 to 25 bar steam pressure, 450°C steam temperature;

– compound operation without simple expansion and without direct injection into the receiver;

– utmost internal streamlining of which perhaps the most significant is that applied to the piston valves;

– advanced valve and piston tribology;

– advanced draught ejector design (halved back pressure for a given draught as compared to the KYLCHAP or GIESL ejectors) including the Kordina effect;

– economizer;

– feedwater and air heating by exhaust steam;

– Gas Producer Combustion System (GPCS) with cyclonic flame path;

– advanced feed water treatment;

– "exaggerated" cylinder and boiler heat insulation;

– elimination of wall effects in the cylinders;

– virtual elimination of wall effects;

– new concepts concerning compounding;

– elimination of the "dynamic augment";

– high rotational speed (504 rpm, AAR standard 1947);

– ergonomic operation;

– compliance with environmental protection regulations etc.

The above list should be completed by a myriad of details which together enable the **harmonious** operation of the various thermodynamic and mechanical components, each of which is integrated into that admirable conception which is the STEPHENSONian locomotive. One should at this point remember its fundamental characteristics as **currently** understood:

- a cycle in which the steam, after having worked in the cylinders, is released into the atmosphere (no condensation);
- a draughting system consisting of static, non-moving parts which keeps the steam/air ratio constant over the whole boiler operating range, hence no boiler controls;
- a boiler which has a very high specific evaporation (up to 140 kg/m^{2}h);
- a direct connection between the power pistons and the wheels (the connecting rod);
- no recourse to electricity and/or gears for power transmission;
- a boiler which forms the structural backbone of the engine;
- a rigid wheelbase leading to least forces exerted on the track;
- a non-enclosed motion;
- a performance not dependent on advanced metallurgy;
- a cab for the driver/crew which is protected against collision;
- a well adapted, natural tractive effort curve;
- no automatics required for driving;
- well trained, experienced drivers/crews necessary;
- it is not repaired by the replacement of spare parts, but by the reconstruction of worn-out components;
- it carries the energy and water supplies with it;
- an indefinitely long life etc.

XXIst Century Steam continues to keep to these fundamentals, albeit altered and improved. So, what makes the difference? The answer: **thermodynamics**. In reference to which BULLEID, the last of the English giants, said [2]: "It never sold a single locomotive."

Most importantly of all, it requires an investment per hp which is about a third of that necessary for an equivalent diesel fleet, not to mention its ability to work on a wide range of fuels.

4 Thermodynamics

A locomotive operates on the basis of extremely complex thermodynamic phenomena. This is true of most machines: an aeroplane also uses extremely complex aerodynamic phenomena. The point remains however that the following principle applies:

Nobody knows what he does not know until he knows it.

The English-speaking world behaved as if thermodynamics did not exist: this explains why BULLEID made the remark quoted above. Yet his post-WWII Pacifics ran daily at 130 km/h (80 mph), and a maximum of 200 km/h was reached by DRG's 05 and GRESLEY's A4.

The steam locomotive was already an admirable machine **before** scientific thermodynamics reached the engineering community. Its development progressed mainly by trial and error on an empirical basis. Long before **any** quantitative analysis was possible, the British were, as early as 1895, able to run the 869 km between London and Aberdeen in 8 h 29 min with three stops made during the night. The empirical genius of those engineers was however insufficient to produce, after WWII, engines which performed significantly better than pre-war KINGS for example, whilst at the same time their fellow engineers working on

[2] Click, J.: Personal communication, 1977.

aeroplanes had invented the jet. Mention should be made of the unhappy efforts of GOSS and YOUNG in America: the former took the "loss of tractive effort at speed" as inherent to the very nature of the steam locomotive, whilst the latter, after considerable theoretical and experimental work, achieved those worst-ever ejectors characteristic of most American locomotives: a thundering exhaust and a 3 m column of solid black smoke were far from correlating with power and efficiency!

Although the names of GARBE and STRAHL must be cited for the Continent, it was not until the work of CHAPELON appeared in 1938 [[3]] that a clear understanding of what a steam locomotive is became reality. Unfortunately, he wrote in French, not in English. His tremendous step forward was therefore a cry in the dark. It was not until after WWII that the British showed a blast of genius in understanding what a steam locomotive is, namely a machine to convert chemical energy into mechanical work: ELL was the new hero [[4]].

Thermodynamics does not however simply mean the description of the locomotive in terms of the theoretical heat engine affected by suitable coefficients as required to adjust it to practical experience. It is much more: it is to describe each of the particular phenomena as related to engineering fundamentals. This should make it possible to predict the work of each one of the parts.

Prediction based on such fundamentals is the key to progress because the designer can manipulate all the involved factors so as to achieve the most convenient result.

An example of such a prediction of performance is the formula for the pressure drop between the steam chest and the cylinder in piston valves at a given cut-off:

$$\frac{\Delta_p}{p_s} = \frac{4\varepsilon(1-\varepsilon)}{2\varepsilon(1-\varepsilon) + \sqrt[3]{0{,}8v \bullet \gamma \bullet p_s \left[\frac{(\varepsilon_0+\varepsilon)(V+2e\varepsilon)}{0{,}71+1{,}5\varepsilon} \bullet \left(\frac{b \bullet my \bullet 100}{j \bullet u \bullet \pi \bullet \beta}\right)\right]^2}}$$

where Δp [bar] pressure drop at cut-off ε; p_s [bar] steamchest pressure; ε [-] cut off; v [m^3/kg] steam specific volume; γ [-] coefficient to account for steamchest pressure oscillations; ε_0 [-] clearance volume/cylinder volume; V [cm] lead; e [cm] lap; b [cm] port length (circumferencial); μ [-] contraction coefficient of the stream at port opening; j [dm^3] cylinder volume; u [1/s] revolutions per second; β [-] coefficient to account for wall effects.

A design aim should be to have Δp as small as possible. The above formula was developed by STRAHL in 1924 [[5]], later modified by the author. The influence of the various parameters is quite apparent so that the designer can play with them to the best advantage. Thus a large lead V, a large valve diameter (i.e. a large b), a large contraction coefficient μ, a low β (condensations!), small oscillations (γ) etc. can be quantitatively treated. How far is all this from the vagaries of the "long valve travel" of the GRESLEY era! All this was not even suspected in the English-speaking world. SCHÜLE treated these phenomena as early as 1906 [[6]].

In addition, the engineer must combine all relevant factors so as to produce a "commercially successful" machine – and nothing less! For certain, this is not textbook thermodynamics. The above formula is an example. What it represents should be extended to the myriad of phenomena occuring in a locomotive. This is not that machine of such a dazzling simplicity that most people (including most engineers) believe it to be. Fortunately for XXIst Century Steam, the computer makes a manageable matter out of it.

3. Chapelon, A.: La locomotive à vapeur. BAILLIÈRES et FILS, Paris, 1938.
4. Ell, S.: Paper No. 235. J. Inst. Locomotive Engineers, 1953.
5. Strahl, G.: Der Einfluß der Steuerung auf Leistung, Dampf- und Kohlenverbrauch der Heißdampflokomotiven. Hanomag-Nachrichten-Verlag G. m. b. H., Hannover-Linden, 1924, on p. 99.
6. Schüle, W.: Zur Dynamik der Dampfströmung in der Kolbendampfmaschine. ZVDI 1906, pp. 1900, 1934, 1988.

5 The GPCS (Gas Producer Combustion System)

The GPCS is described in [7]. It essentially consists in transforming the firebed into a gas producer by making it very thick. Only 30 % (20 % in the case of biomass) of the combustion air passes as primary air through the grate, thus leading to an almost negligible particle entrainment. The secondary air makes up the lion's share of the air needed for combustion and creates an intense turbulence in the flame space so that the gas phase combustion can proceed to the degree of completeness required to meet pollution laws. While it appears to have that extreme simplicity characterizing great inventions, its thermodynamics are extremely complicated – after all just an intellectual problem!

The GPCS started to be developed in 1958 by the author in connection with the use of coal as fuel. But concerning XXIst Century Steam, its great merit is that it leads to a simple, most efficient use of **biomass** as locomotive and industrial fuel. Any kind of biomass may be used, as proven by tests in 1963 [8]. So far, the following fuels have been successfully fired: firewood in logs, sawmill rejects, bagasse (in stationary boilers), a wide variety of coals, bagasse-oil briquettes, charcoal fines mixed with oil etc. In the near future, rice husks, orange peels, bark, and dry peat will be tested. One of the blessings of the system is that smoke disappears. In 1963, tests were successfully carried out with charcoal fines (0-6 mm) under fluidized bed conditions. CO- and HC-emissions virtually disappear, and NO_x-emissions are very close to their theoretical minimum. The expectancy is that, by simply blending the fuel with a calcite-dolomite mixture, sulphur can also be controlled to a large extent.

6 Biomass as a railway fuel

During WWII, the author worked as a fireman on locomotives originally designed for coal, later converted to burn wood in log form. The sole modification was the suppression of the brick arch. No change in the performance was detectable provided that the firewood was seasoned so as to reduce the high initial moisture content, while for heavy services certain species were preferable because of the need to limit the physical effort of the fireman. As proven by the 1963 experiments, and later in Paraguay (in 1988), the GPCS gave complete satisfaction as a first class locomotive firing system. Developments in hand consist in mechanizing the feed by hogging the fuel, thus enabling it to be handled in bulk: any level of power can be developed.

Energetic plantations are not a novelty. The driving force behind them is that the CO_2 produced by the combustion of firewood comes from the fixing of the atmospheric CO_2. Thus no additional CO_2 is liberated to increase the greenhouse effect, a matter of **major concern**. Transportation is one major offender, and the possibility of reducing CO_2-emissions to a great extent thanks to the use of biomass must be considered as a great contribution to environmental protection. By no means is this limited to railways.

7 Mechanical and Operational Aspects

While advanced thermodynamics is a key element of XXIst Century Steam, other aspects of locomotive engineering are by no means less significant because they encompass all that must be done in order to convert theory into the actual economical pulling of trains. Perhaps the most important one is feed water treatment. Since 1944, the French TIA system guarantees an indefinite life for the boiler to the point that it can be welded on to the frame. Pure steam (contamination < 1 ppm) also guarantees an indefinetely long life of the superheater and reduces the abrasive wear in the cylinders. The advances made by the author since 1970 are reflected in the fact that the treatment is cheap and **heavy duty**, a most important characteristic for the Third World [9].

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7. Porta, L. D.: Exemple d'une technique de progrès: la combustion gazogène. Conference de l'ICOHTEC, Paris, 1992.
8. Porta, L. D.: Tests on the combustion of wood rejects and charcoal fines, Gas Producer Combustion System. INTI Document, Buenos Aires, 1963.
9. Porta, L. D.: Steam locomotive boiler water treatment. 1975, revised 1987 (unpublished).

The following mechanical improvements are considered:

- roller bearings throughout;
- manganese axlebox rubbing surfaces;
- piston and valve rings lasting 1,000,000 km with perfect tightness;
- substitution of the crosshead mechanism by links;
- grinding the tyres every month without dismantling the wheels or the motion;
- virtual supression of atmospheric corrosion;
- advanced packings for valves etc.;
- most important of all, attention to **detail** design: 50 % of daily maintenance is devoted to details!

The fuel and water consumption is expected to be reduced to **one fourth** of what old steam locomotives (generation zero) show. This results in much longer runs between stops to take water and fuel. In shunting duties, the fuel consumption should equal the diesel one. Last but not least, a most elaborated **ergonomy** should be achieved for all concerned.

8 Third Generation Steam

The possibilites of XXIst Century Steam are not exhausted with the previously described listing. Should the thermal efficiency issue become even more pressing, Third Generation steam locomotives could reach 21 % under test conditions, of course using biomass as fuel. The improvement is on the thermodynamic cycle:

- 60 bar/550°C steam;
- triple expansion;
- regenerative three stage feed water and air heating;
- other detail improvements etc.

All still keeping to the STEPHENSONian scheme.

Should it prove to be interesting, a further advance in thermal efficiency, a condensing scheme, could be envisaged. This condensation should occur in a "cooling-tower" tender like the SLM-ESCHER WISS machine (ca. 1926). The water treatment can be modified to accept raw water as boiler feed because the condenser is of the evaporative type. Optimistically, the overall thermal efficiency could reach 27 % at the drawbar.

9 Examples

To avoid speaking about entelechies, Figs. 1a/b and 2 are two examples of XXIst Century Steam. Fig. 1a/b is a small 1,000 hp engine for shunting and branch line services, whereas Fig. 2 is a 8,000 hp fast freight engine for American or Russian conditions. The hp figures are to be interpreted in terms of equivalent-to-diesel power. An infinite variety of designs could be imagined, although a spectrum of limited alternatives could probably cover 90 % of the actual requirements. All of them are to be fired with biomass, hence environmentally clean.

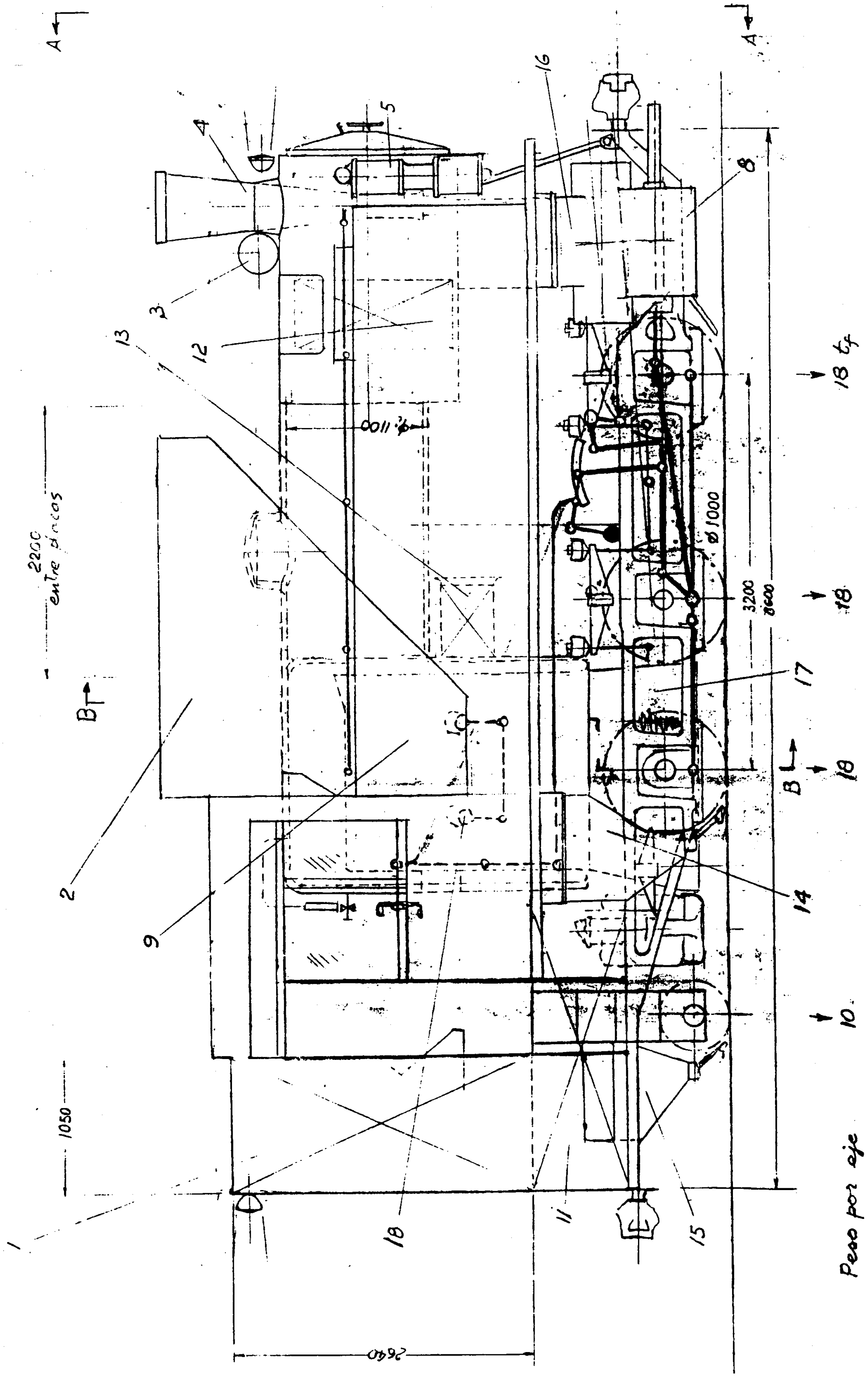

Fig. 1a: Shunting and branch line 3-cylinder compound locomotive.

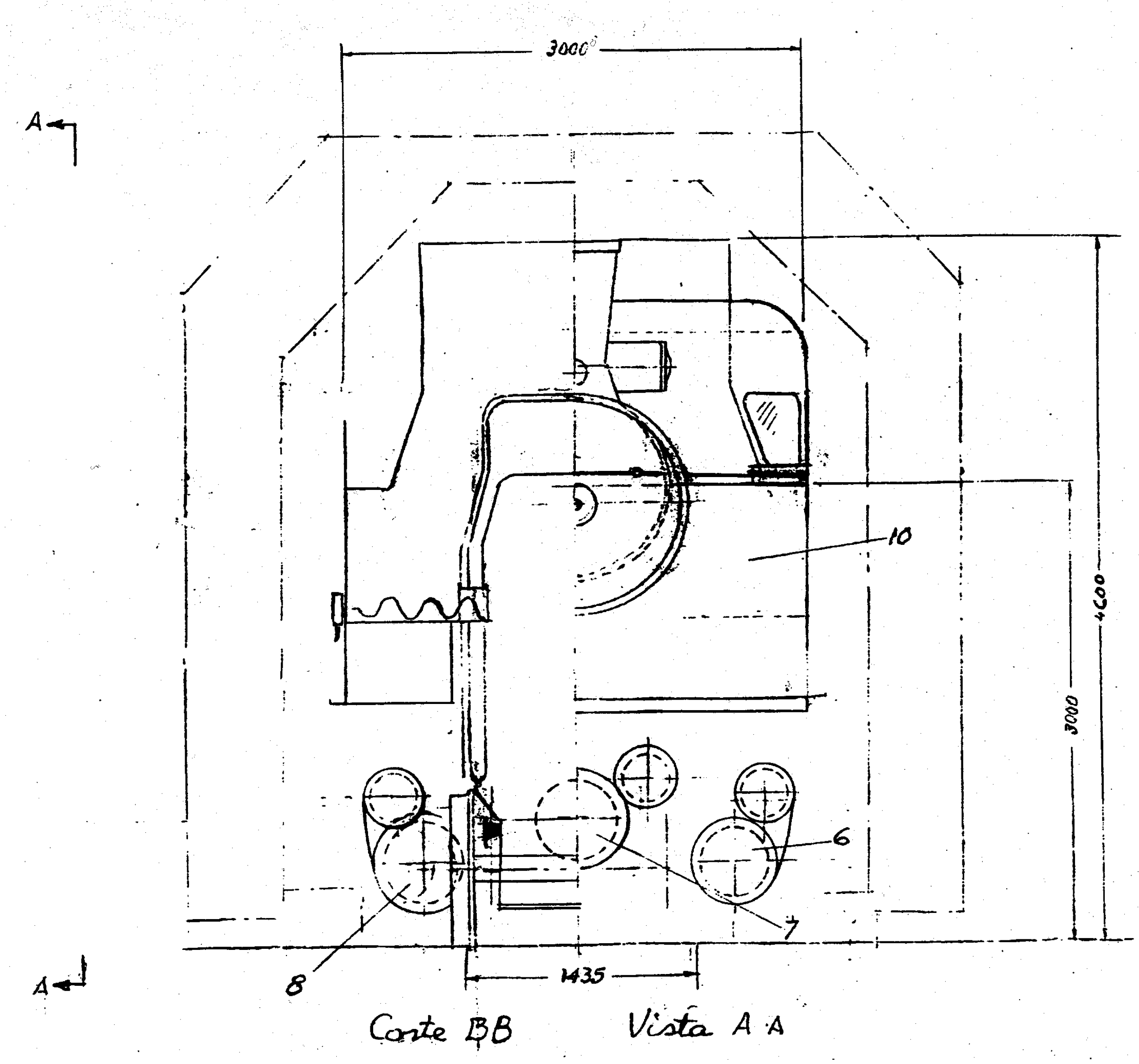

Fig. 1b: Shunting and branch line 3-cylinder compound locomotive.

1	Fuel space	6 m^3	10	Water tank	12 m^3
2	Fuel space	6 m^3	11	Water tank	6 m^3
3	Feed water heater	6 m^2	12	Economizer	
4	LEMPOR ejector		13	Air pre-heater	
5	Air pump		14	Sand box	
6	LP cylinder	(512 x 550)	15	Sand box	
7	HP cylinder	(440 x 550)	16	Sand box	
8	LP cylinder	(512 x 550)	17	Ash box	
9	Gas producer cyclonic firebox		18	Fuel inlet	
			19	Main air reservoir	

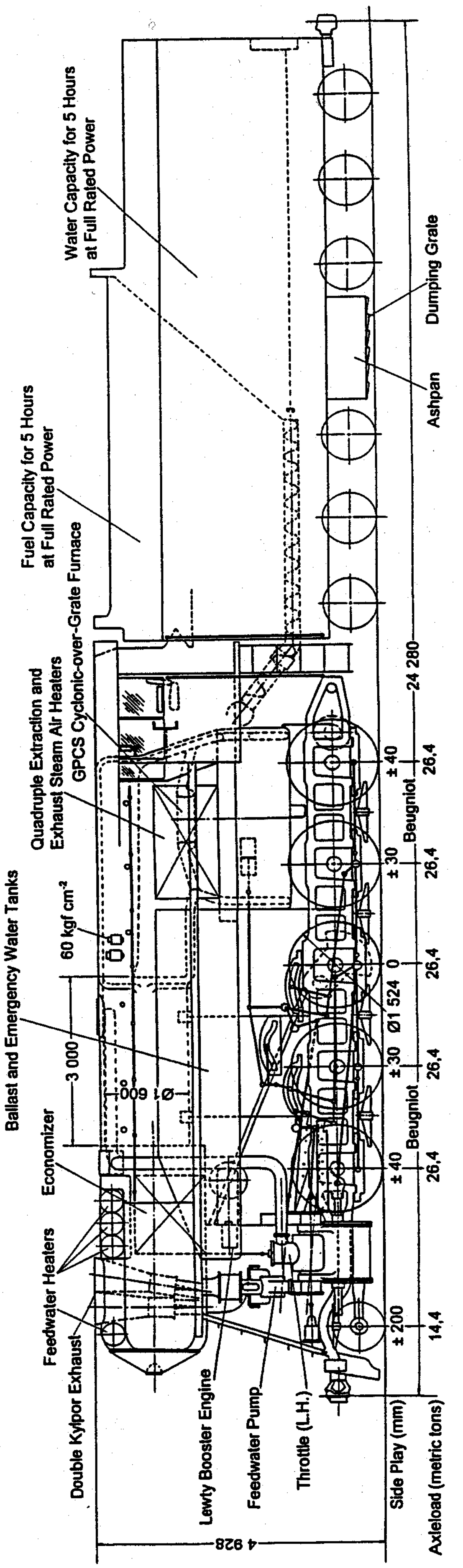

Fig. 2: Third Generation fast freight 8,000 hp locomotive.

The STEPHENSONian configuration is adhered to. The high thermal efficiency leads to a very small boiler for the high power output and a reasonably sized tender for 500 km non-stop runs. The locomotive is ballasted because of the very high power-to-weight ratio.

Although the 8,000 hp incorporate a special form of booster giving a very high tractive effort at low speeds, one should note that the generalization of roller bearings for the cars reduces the need for a high starting tractive effort. As seen, the familiar appearance of the STEPHENSONian locomotive continues to be the choice. Many people will be disappointed because they cannot perceive anything but bogies, individual axle drives, water tube boilers, electric drives etc. But the question is first one of thermodynamics, thereafter how this thermodynamics is transformed into a successful machine. They should point out what cannot be done within the proposed scheme as compared to the presumable advantages of the non-STEPHENSONian solutions. But, in the meantime, they should not forget the non-convincing or poor performance (in some cases to the point of utter failures) of the following engines:

- various Henschel-Schmidt (special cycle, water tube firebox, Germany, England, Canada)
- SLM 2-6-2 (60 bar, uniflow single expansion motor 1926)
- SNCF 232 P I (water tube firebox, two pressure cycle 60 and 20 bar, individual axle drive)
- LNER 10 000 (water tube boiler)
- DR-Schwartzkopff-Löffler (special cycle, high pressure)
- PLM 230 E 93 (Velox boiler)
- DR 45 024 (La Mont boiler, condensation, pulverized coal)
- three machines of the Delaware & Hudson (water tube firebox, high pressure)
- Sentinel for Colombia (water tube boilers, bogies)
- SNCF 232 Q I (turbine, individual drive)
- Heilmann, 1893 (steam electric)
- LMS Paget locomotive (individual motors)
- Egyptian Railways' Sentinel (individual motors)
- Lübeck-Büchener Railway's No. 71 (V-motor drive)
- DRG 19 1001 (individual motors)
- BULLEID's Leader (bogies)
- BULLEID's Leader (bogies, Ireland)
- SNCF-DABEG 221 TQ 1 (12 cylinder motor)

A number of turbine locomotives is to be added to this list of failures, which should be studied to avoid the repetition of mistakes. Why, in spite of a predictable failure, were some engines built?

10 Additional considerations and recommendations

It is impossible to summarize, for the uninformed reader, what XXIst Century Steam is. When one considers that for most people even CHAPELON's work is unknown, never mind understood, the gap to be bridged is enormous: lack of information has been a plague in the past. This is certainly not the case for the automotive industry where everybody knows what everybody else is doing as a must for successful competition. Furthermore, such information is essential in order to make investment decisions; for nobody will invest in what they do not understand. **Nobody likes the unknown!**

A second difficulty is that no masterpiece can be produced according to a recipe, as is the case for a cookery course: **talent** is essential, and the lack of it may explain some of the listed failings.

A third difficulty is the lack of a driving force: **who will convert the above technicalities into a large-scale business?**

11 Main conclusions on steam locomotives as railway motive power

1 A **XXIst Century Steam** railway motive power already exists in full development.

2 This motive power shows **clear advances and advantages**:

2.1 It uses **non-polluting biomass**.

2.2 It is compatible with the culture and recources of **both the First and the Third World**.

2.3 It is based on **most advanced applied thermodynamics** and **gasification of solid fuels**.

3 By using **standardized components** as much as possible for various classes, **economies of scale** and thus **low unit prices** can be achieved.

4 A **great business** is just around the corner to provide steam motive power for the **railway boom** just starting in the Third World.

2 - Tracción a vapor moderna y sostenible – el escenario cubano

José Olmo Pérez

Resumen: En el mundo actual hay un marcado esfuerzo de muchas personas e instituciones por mantener vigente la magia y poder de la locomotora a vapor, pero sobre todo, la tendencia es a conocerla como una reliquia histórica que ha despertado especial atención para un mercado vinculado con intereses turísticos y culturales.

Esta alternativa, sin dejar de ser atractiva para los posibles objetivos turísticos, se debería conjugar además con una política racional para el desarrollo sostenible de los sistemas de transportes públicos e industriales en base a la tracción a vapor moderna. La implementación de un programa integral orientado a introducir en los ferrocarriles de todo tipo, la moderna tracción a vapor es una contribución al ferrocarril del nuevo siglo y una propuesta de espacio ante la alta velocidad y los grandes trenes de carga adecuados para los nuevos retos del mercado de transporte.

La nueva tracción a vapor moderna dada la versatilidad de utilizar, tanto combustibles fósiles como, combustibles alternativos permitirá mantener en explotación bajo cualquier circunstancia parte del sistema ferroviario de un país sin necesidad de una dependencia total de petróleo importado, reduciendo gastos en repuestos diesel cada vez más costosos.

Las locomotoras a vapor modernas (o de nueva generación) combustionando mediante gasificación de la biomasa renovable, son neutras en emisiones de CO y NO_x e incluso consumiendo petróleo o gas reducen en un alto nivel la contaminación ambiental respecto a las diesel.

Durante 160 años, las locomotoras de vapor han estado presentes en los ferrocarriles cubanos. Hasta los años 50 era nuestro principal modo de tracción. Aún hoy se pueden ver funcionando unas 200 locomotoras de vapor de principio de siglo, en casi el 60 % de los centrales azucareros localizados en el territorio nacional. El Grupo IT (Asociación de Investigación y Producción del Transporte) está promoviendo y ejecutando el denominado Proyecto Prometeo, mediante un programa de modernización de estas locomotoras y un proyecto novedoso de construcción de máquinas de nueva generación bajo conceptos del vapor moderno.

La locomotora No. 1816 ALCO (2-8-0) fue modernizada y se encuentra puesta a prueba en Cuba a base de fuel-oil en una primera fase y biomasa en una segunda (bagazo de caña de azúcar compactado).

Una situación especial para Cuba es que coinciden todas las condiciones para desarrollar esta novedosa tecnología que por cuestiones coyunturales hicieron que el vapor tradicional no avanzara en otros países.

Promover la llamada **Tracción Verde** con locomotoras ecológicas se traduce en valioso aporte a la protección ambiental de nuestros países para un desarrollo sostenible y compatible con el bienestar que reclama la humanidad ante los umbrales del Siglo XXI.

1. Antecedentes y desarrollo de la tracción a vapor en el mundo.

La historia de este tipo de tracción mecánica comenzó en 1830, con el primer ferrocarril interurbano, entre Liverpool y Manchester. Por primera vez aparecían reunidos todos los elementos de un ferrocarril moderno.

Transcurrida una docena de años las velocidades de los trenes se habían duplicado, mientras el peso de las locomotoras se había triplicado, la potencia que desarrollaban se había cuadruplicado y se había alcanzado un grado aceptable de fiabilidad. Además, habían surgido dos tendencias de desarrollo bastante distintas a uno y otro lado del Océano Atlántico.

La máquina de vapor contó entre sus primeras aplicaciones en los medios de transporte, no solo ferroviario, sino también el marítimo-fluvial e incluso el automotor. Sin embargo, esta tecnología, tras largos años de desarrollo, se ”durmió ”a pesar de estar aún bien distante de las posibilidades que las leyes de la termodinámica le concedían.

Con la aparición en el pasado siglo de la locomotora de vapor, el mundo cambió en pocos años al reducirse a una tercera parte o menos el costo y duración de los viajes. La locomotora de vapor marcó en muchos países el verdadero comienzo de la civilización; el ferrocarril marcó las pautas del futuro desarrollo económico de muchos países; Cuba es uno de los ejemplos mas fehacientes de ello, como lo fueron también los Estados Unidos y algunos países europeos.

Sin embargo, la locomotora de vapor clásica no asimiló los avances de la termodinámica y de la tribología que a partir de los años 50 fue desarrollando impetuosamente la tecnología diesel y fue finalmente desplazada por esta. Los trabajos de ingenieros franceses y alemanes de la preguerra para revolucionar la tecnología de la locomotora de vapor nunca se generalizaron. Alemania perdió la guerra, y Francia tuvo que depender de tecnología clásica, suministradas a través del Plan Marshall como ayuda de los EE.UU. para rehabilitar los ferrocarriles franceses conformados entonces por unas 1500 locomotoras de vapor.

En 1926 un científico francés llamado Andre Chapelon había demostrado que la locomotora de vapor convencional era susceptible de progreso si se modificaba su diseño empírico por la termodinámica.

Del otro lado del Atlántico un joven ingeniero argentino, Livio Dante Porta, hace 50 años tuvo acceso a las innovaciones que el francés Chapelon y los científicos alemanes habían desarrollado; las aplicó en el prototipo de una nueva locomotora de vapor y después en la transformación de locomotoras japonesas adquiridas en los años 50 para el ferrocarril carbonero de Río Turbio, en la Patagonia.

Este entonces joven ingeniero logró duplicar el rendimiento de sus máquinas en términos de unidad de trafico producida por unidad calórica consumida, y eliminó la mayor parte de los problemas que caracterizaban a las tradicionales locomotoras de vapor de ineficientes.

Los trabajos del ingeniero Porta y su tecnología innovadora, le dan fama mundial, y se llegaron a aplicar en la modernización de locomotoras de vapor en Sudáfrica, Gran Bretaña, Sudan, Brasil, Paraguay. Ante el alza de los precios del petróleo a principio de los años 80 se desarrolló en EE.UU el Proyecto ACE 3000 para la fabricación a gran escala de 17000 locomotoras de vapor ultramodernas, a carbón, figurando el ingeniero Porta como artífice principal de este proyecto.

Estos trabajos son ampliamente recogidos por la prensa especializada ante la realidad del fin de la era del petróleo barato. Pero no pueden desplazar el dominio que la tracción diesel ya había alcanzado.

La nueva baja en los precios del petróleo liquidó el Proyecto ACE 3000, que contaba con fuerte respaldo del gobierno de los EE.UU. con Porta como proyectista principal.

La nueva concepción del ingeniero Porta sobre la locomotora de vapor moderna en base a la tecnología de Chapelon, se basa en los sencillos principios de la invención de Stephenson (una caldera humotubular, una máquina de vapor, y pistones que trasmiten la fuerza a las ruedas mediante bielas) pero en una mucho mas perfeccionada termodinámica.

Es una técnica radicalmente nueva, aplicable a la modernización de locomotoras de vapor, por el diseño de su caldera, que logra una combustión prácticamente total, eliminando o reduciendo al mínimo la contaminación, su aerodinamismo interno, nuevos conceptos en el aparato de tiro, un optimo aprovechamiento del vapor generado a mayores o muy altas presiones, en sus cilindros se aplican los avances tribológicos más actuales, y el perfeccionamiento de todos los mecanismos que pueden constituir perdidas de potencia o fuentes de averías.

Entre los antecedentes de la aplicación a escala internacional de esta tecnología del vapor moderno están los siguientes:

1952 Construcción de una locomotora experimental de trocha estrecha tipo 4-8-0 FCGB, potencia medida en el gancho 2120 hp. Récord mundial de potencia por unidad de masa (31 hp_e/t) y de consumo específico de combustible (810 g/hp_e-h).

1953 Doce máquinas del tipo 8C, zona local, FCGR construidas en 1915. Modernización liviana. Estas máquinas con dos cilindros eran capaces de prestar mejor servicio que las 8E de tres cilindros.

1952-1957 Aproximadamente 50 locomotoras del tipo 8E FCGR construidas en 1927. Modernización liviana. Se logró un incremento de potencia de aproximadamente un 30 % y una mejora en el consumo de un 5 %.

1955 Modernización de la locomotora 3477. Construidas en 1915. Prototipo de modernización pesada de la serie 8C, servicio local FCGR. Con esto se logró un 80% de incremento de potencia a 100 km/h, hasta 1350 hp_e.

1956 Tres locomotoras locales tipo 30 ex-CGBA (PBA) construidas en 1906, trocha estrecha, modernización liviana. Se alcanzó un incremento en la potencia de aproximadamente 80 %.

1957 Una locomotora HUNSLET para el Puerto Capital en Argentina. Modernización liviana.

1962-64 Veinte locomotoras nuevas construidas en Japón entre 1955 y 1963, modernizadas para el ferrocarril de Río Turbio. Se logró un incremento de potencia de un 30 a 50%.

1969 Prototipo de locomotora 1802 serie C16 FCGB. Modernización liviana. Se alcanzó un incremento de potencia de 1100 hp_e a 1600 hp_e y un incremento de la productividad del combustible de aproximadamente un 70%.

1958-61 Prototipo de locomotora No. 4674. FCGB. Modernización pesada con la que se logró un incremento de potencia de aproximadamente 50%.

1982 Prototipo de locomotora No 2644 serie 19D perteneciente a los South African Railways. Modernización pesada ejecutada por el Ing. D. Wardale. Se alcanzó un incremento de potencia de aproximadamente 50%.

1983 Prototipo de locomotora No 3450. Serie 25 NC, perteneciente a South African Railways. Modernización pesada ejecutada por el Ing. D. Wardale según tecnología PORTA. Se logró un incremento de potencia de 2800 a 4000 hp_e y el consumo de combustible en tráfico ordinario se redujo en un 30% aproximadamente.

En el mundo hay una 20000 locomotoras de vapor localizadas en China, India, Sudáfrica, Polonia, Malasia, Cuba, Paraguay, Brasil, Zimbabwe, y en menor escala en muchos otros países. A partir de 1970 siguió la revolución de progreso silencioso del vapor moderno. En la última década la prestigiosa firma suiza SULZER-SLM ha estado ofertando y construyendo sus nuevas locomotoras de vapor H 2/3 para los ferrocarriles de cremallera en los Alpes Suizos.

Actualmente los servicios turísticos ferroviarios cobran relevante fuerza en todo el mundo, pero son especialmente los trenes movidos con locomotoras a vapor y vinculados a circuitos de interés turístico y cultural en determinadas regiones los que gozan de pleno vigor en los últimos años.

Hoy en día pueden verse locomotoras a vapor en circuitos turísticos en países tales como: China, Austria, Bélgica, República Checa, Francia, Alemania, Holanda, Italia, Latvia, Noruega, Polonia, Rumania, España, Suiza, Ucrania, Africa del Sur, Zimbabwe, India, Jordania, Estados Unidos, Argentina, Australia y Nueva Zelandia.

La máquina de vapor debe renacer hoy como un modo ecológico de transformación de energía. En los ferrocarriles de muchos países surge el vapor moderno caracterizado por la locomotora energéticamente sostenible, como una alternativa no solo para la tracción Diesel, sino incluso para la tracción eléctrica sobre todo cuando la intensidad del servicio no permite soportar los altos costos de sus instalaciones.

2. La nueva tracción a vapor y su integración en los ferrocarriles del mundo.

Los ferrocarriles de cualquier país necesitan una fuerte inyección de divisas para inversiones y para su mantenimiento, muy por encima de sus posibilidades, para poder sostener su misión como parte del Sistema Nacional de Transportes. En los ferrocarriles de muchos países se presenta el fenómeno de dependencia económica formado a través de la implantación paulatina de la dieselización basado en la idea de un progreso irresistible, pero a su vez, con un fuerte compromiso para sus economías.

Cabe mirar el tema desde el punto de vista del negocio. En tanto que con el vapor el fabricante lo terminaba con la venta, con el diesel recién lo empezaba, siguiéndolo con los repuestos que dan al usuario ferroviario el carácter de cautivo. Y cuando termina de pagar la máquina luego de su corta vida se encuentra que debe seguir poniendo dinero para reiniciar el ciclo con una nueva compra o con un fuerte proceso de remotorización de sus unidades.

El servicio de tracción y sus equipos, por lo general representan la mayor parte de las inversiones en cualquier esquema de rehabilitación o simple sostenimiento de un ferrocarril. La fluctuación de los precios del gasoil es otro factor a tener en cuenta en el costo de la tracción, así como tampoco es despreciable el costo de lubricantes cada vez más caros. El gasto principal en el sostenimiento de un parque ferroviario diesel está dado por la demanda sistemática de divisas para partes y piezas. Se estima que una locomotora diesel necesite entre un 2 y un 3 % de su valor anualmente para partes y piezas. Por otra parte, según los actuales precios internacionales, por una locomotora diesel, por ejemplo de 1000 hp, representaría a un ferrocarril tercermundista invertir mas de un millón de US $.

Muy pocas líneas ferroviarias en el mundo admiten los costos de electrificación, aún en el caso de que se disponga de energía barata. En este marco, cabe considerar además, los gastos energéticos totales unitarios incluyendo no solo el gasto energético de la locomotora, sino valorando también los gastos energéticos de las instalaciones de generación de la energía, las perdidas de transmisión, la consumida en la fabricación de los equipos y las perdidas externas de este hasta convertirse en trabajo útil.

Para países donde existen locomotoras de vapor en operación (Cuba, China, Paraguay, Indonesia, La India, Sudán etc), la modernización puede ser una alternativa, sin obviar la adquisición de locomotoras de vapor modernas llamadas de nueva generación. Para países donde ya no exista el vapor, la locomotora de vapor moderna puede ser una opción, restableciendo o mejorando sus servicios de menores tráficos (maniobras y trenes ligeros).

Está demostrado que la tracción moderna de vapor es comparable y en ocasiones mas eficiente desde el punto de vista del costo energético primario por kgf de esfuerzo de tracción en la llanta. Una estrategia de modernización de locomotoras de vapor, activas o paralizadas puede ser llevada a cabo en función de un esfuerzo inversionista dado, desde un mínimo hasta una máximo. Un alto % de las locomotoras de vapor que existan en cualquier país pueden ser reconstruidas y modernizadas para una nueva vida útil de no menos de 20 años (la vida útil de una locomotora diesel nueva), a un costo en divisas tres veces inferior a una reparación capital de una diesel, cuatro veces menos que el costo de una diesel de uso y 20 veces menos que la inversión en una diesel nueva.

La nueva tracción a vapor moderna permite mantener en explotación en cualquier circunstancia parte del sistema ferroviario de un país sin necesidad de petróleo importado, ni lubricantes caros ni partes y piezas de repuesto diesel cada vez más costosas, alternativa económica nada despreciable para nuestros países. De ser necesario adquirir locomotoras nuevas, los costos de inversión por hp en nuevas locomotoras de vapor son varias veces menores que en la tracción diesel. Las locomotoras de vapor pueden trabajar con fuel-oil, crudo bituminoso, cualquier tipo de biomasa compactada, leña o gas, alternativas que independizan el sistema ferroviario de coyunturas políticas o especulativas tan vinculadas al mercado petrolero.

Si el ferrocarril existe en nuestros países donde los niveles de eficiencia fluctúan con altas y bajas, lo esencial entonces es hacerlo trabajar. La alternativa de eliminación como sistema siempre será mas cara, socialmente, ambientalmente, e incluso económicamente. Consolidar su parque tractivo para satisfacer servicios altamente demandados, y convertirse en empresas financieramente sanas es la variante en uso en los fines del Siglo XX.

La ventaja de un programa integral, orientado a introducir en los ferrocarriles de todo tipo, (no solo en los turísticos) la tracción moderna es un aporte al nuevo ferrocarril del siglo XXI. La alta velocidad y los super - trenes de carga, adecuados a países de alto desarrollo ferroviario, tendrán espacio, pero la alternativa de los ferrocarriles restantes necesitarán de una solución económica sostenible como podrá ser con la denominada ”Tracción Verde” o Tracción a Vapor Moderna.

Otro aspecto relevante a considerar es la contribución que se pueda hacer a la protección del medio ambiente. La nueva tracción de vapor puede trabajar totalmente con biomasa, (leña, leña plantada, leña troceada, residuos de aserradero, residuos del bosque, residuos agrícolas o agroindustriales, bagazo de caña compactado, por ejemplo). Puede usar lubricantes de origen vegetal, con la excepción del aceite para los cilindros. Su tratamiento de agua se puede hacer con productos de alta integración nacional y biodegradables.

Las locomotoras de vapor, modernas o modernizadas, habilitadas para combustionar por gasificación de biomasa, serán neutras en cuanto al emisiones de CO, y de NO_x, e incluso, consumiendo petróleo, reducen en varias veces la emisión de contaminantes nocivos en comparación con las locomotoras diesel. Esta experiencia fue obtenida por la Universidad de Munich, en pruebas con locomotoras de vapor modernas construidas por SLM de Suiza.

La introducción de la nueva tracción a vapor en el esquema de transporte sostenible de un país, permite mejorar su entorno socio-económico al proporcionar nuevas fuentes de empleo y poner en tensión sus potencialidades fabriles, pudiendo aportar instalaciones y mano de obra. A su vez, contar con modernas unidades tractivas a vapor requerirá de la creación de empleos al personal de operación (manejo y mantenimiento), así como, para la preparación profesional de dicho personal y determinada asistencia técnica a esta novedosa tecnología.

3. El vapor cubano y el desarrollo ferroviario nacional.

El surgimiento y desarrollo del ferrocarril cubano en el siglo XIX es parte fundamental de la historia de nuestro país y del mundo. Cuba fue el sexto país en fundar su ferrocarril y el primero de Iberoamérica (1830).

Las necesidades económicas que habría de satisfacer el ferrocarril y que determinaron su temprana introducción, como su posterior difusión, conformó un aspecto esencial en el fenómeno histórico ferroviario de nuestro país. A diferencia de lo que sucedió en otros países, el ferrocarril en Cuba se desarrolló para facilitar los vínculos de los productores insulares con los mercados exteriores. En el marco de una entonces economía monoexportadora, el empleo del ferrocarril estaría determinado por las necesidades del principal y casi único producto exportable: el azúcar.

Hacia 1830, el problema del transporte terrestre constituía el punto crítico del ciclo azucarero. Ante las pobres perspectivas que ofrecían los medios de transporte convencionales, el ferrocarril constituyó la solución salvadora para los productores azucareros cubanos. Esto incentivó la construcción de una vía férrea que enlazaría el rico valle de Güines con la ciudad de La Habana.

Los ferrocarriles cubanos no pasaron como los de Inglaterra o Norteamérica por las clásicas fases de la tracción animal y posterior sustitución por fuerza a vapor. Como la invención estaba ya plenamente probada en los países industrializados y la urgente necesidad de los hacendados demandaban una solución radical en favor de la exportación del azúcar, este logro de la revolución industrial que era la locomotora de vapor se introdujo en el país con la más acabada tecnología del momento, es decir locomotoras de vapor generalmente de 6 ejes y según las normas de anchos de vía españolas, estas máquinas se caracterizaban por una particular disposición y corta distancia entre ejes que podían correr sin dificultad por curvas de mucho menor radio que las europeas.

A partir de las primeras ”Rockets” del ferrocarril Habana - Güines, el parque tractivo de todas las empresas cubanas se nutrió básicamente con equipos provenientes de Filadelfia, Boston, Nueva York. Ya en 1868 habían en servicio en Cuba unas 176 locomotoras de vapor, combustionando inicialmente leña y, en pequeña medida, carbón inglés o americano.

Las nuevas locomotoras que se construían a partir de 1880, se adecuaban perfectamente a las ventajas que ofrecían otros elementos técnicos novedosos introducidos, como los carriles de acero. Entre las locomotoras preferidas por las empresas cubanas se encontraba el tipo ”Consolidation”, fabricadas en Filadelfia, las cuales tenían una caldera de gran capacidad, un nuevo tipo de válvula compensada más eficiente y 6 ruedas conectadas entre sí, con un velocípedo delantero y ruedas pequeñas en la parte posterior.

La presión máxima efectiva de vapor era de 9,3 kg/cm^2 . Comparativamente estas máquinas eran mejores que modelos anteriores. Sus proporciones permitían incrementar su poder de arrastre en casi un 50 % más que las antiguas más potentes, con solo el aumento del 14 % en el peso y un 35 % en el consumo del carbón.

Es así que durante mas de 160 años, las locomotoras de vapor han estado presentes hasta la fecha en nuestro ferrocarril. Hasta los años 50, era el principal modo de tracción en el país, con excepción de la Línea Eléctrica de Hershey (Casablanca-Matanzas) y alguna que otras locomotoras ”Plymouth” de gasolina y gasoil dispersas en plantaciones cañeras.

Operando sobre diferentes anchos de vía: 56½” (ancho standard en nuestro país y el mas universal), o en vías de las llamadas estrechas: 3', 2'10½”, 2'6” y 2'3¾” pueden verse decenas de diferentes tipos de locomotoras de vapor trabajando en los ferrocarriles cañeros, algo difícil de encontrar en otros países. Los diseños mas comunes de locomotoras de vapor en Cuba son:

- 2-6-0 (MOGUL);
- 2-6-2 (PRAIRIE);
- 2-8-0 (CONSOLIDATION);

y en menor escala las 0-4-0; 0-6-0; 0-8-0 y 2-8-2 (MIKADO).

Aún hoy, mas de dos centenares de locomotoras de vapor sirven trenes en la industria azucarera cubana en donde la tracción a vapor es esencial para 56 Complejos Agroindustriales Azucareros (CAI), a lo largo de todo el país, de los cuales unos 30 operan exclusivamente con tracción a vapor. Aún en las condiciones de deterioro de las locomotoras de vapor actuales, la tracción de vapor tiene menores costos por unidad de tráfico que la diesel según se ha podido constatar en estudios realizados por el Instituto Superior Politécnico (ISPJAE) de la Habana.

4. La nueva tracción a vapor y la actual coyuntura cubana.

Desde el comienzo de la década del 90, nuestro país atraviesa una aguda crisis energética como consecuencia del recrudecimiento del bloqueo económico de los Estados Unidos, el derrumbe del campo Socialista en Europa, y el constante crecimiento de los precios del petróleo.

Se tuvieron referencias internacionales sobre adelantos tecnológicos para una tracción a vapor moderna desarrollados por el Ingeniero Argentino Livio D. Porta, prestigiosa figura internacional en materia de modernización de locomotoras de vapor y la actividad ferroviaria en general, que mejoraban substancialmente la eficiencia energética que fue antaño un argumento en contra del vapor.

El ingeniero Porta fue invitado en 1992 a colaborar con Cuba en la aplicación de su tecnología con el objetivo de reducir la dependencia de los ferrocarriles de la importación de combustible diesel iniciándose así el llamado ”PROYECTO PROMETEO”.

En el caso particular de los Ferrocarriles de Cuba, el parque de locomotoras diesel tiene en su mayoría mas de 20 años de explotación y las limitaciones económicas para adquirir piezas de repuesto o equipos nuevos son cada vez mayores. Según análisis realizados por el Grupo IT, en el Esquema de Desarrollo del Transporte hasta el año 2000, se prevén hacia ese horizonte, incrementos modestos en los volúmenes de transporte de cargas y pasajeros por ferrocarril, no obstante mantenerse las condiciones de periodo especial y arreciarse el bloqueo de EE.UU contra nuestro país. Ante esta situación las capacidades tractivas de nuestros ferrocarriles en su conjunto (públicos e industriales) han sufrido un alto índice de deterioro, casi en su totalidad han vencido su vida útil. Reponer este parque significaría una inversión altamente costosa (se calcula en unos 100 millones de US $) si solo se pensara en locomotoras diesel necesariamente importadas.

Como principio fundamental de esta nueva tecnología se evidencia claramente que la tracción a vapor que se propone no es una regresión a un pasado definitivamente muerto, sino una tecnología que se proyecta hacia el futuro con servicios de gran velocidad y tonelaje bien en consonancia con algo que en Cuba ya hemos hecho, la vía.

La industria azucarera tiene en existencia unas 100 locomotoras de vapor de vía standard cuya potencia y peso harían posible, una vez modernizadas, traccionar cualquier tipo de tren de carga o pasajeros una vez terminada la zafra en situaciones de emergencia o por conveniencia nacional. La industria azucarera cubana en cuanto a la tracción a vapor ha ido delineando en los últimos años una estrategia racional ante las realidades objetivas que enfrenta el país. Hoy, se plantea conservar la tracción a vapor hasta donde sea posible, y gana fuerza la opción de modernización total o parcial de algunas maquinas en función de las experiencias de la locomotora No.1816 totalmente reconstruida.

La recuperación de la producción azucarera en los próximos años demandará la reposición y ampliación del parque de tracción de los ferrocarriles azucareros. La alternativa de hacerlo con locomotoras de vapor modernas construidas en Cuba se presenta como una coyuntura racional. Como una posible solución para paliar la crisis se concibió valorar como la tracción a vapor podría tener un mayor papel dada la posibilidad de las calderas de las locomotoras de vapor de utilizar diversos tipos de combustibles (carbón, leña y fuel oil como mas usuales).

4.1. Locomotoras modernas de vapor para el Siglo XXI energéticamente autosustentables.

Dada la crítica situación que presenta el parque tractivo de los ferrocarriles cubanos cuyo deterioro se ha ido acelerando en los últimos años unido a la subutilización de las capacidades tractivas de este parque han compulsado a las autoridades ferroviarias a buscar soluciones racionales para enfrentar dicha problemática. Estudios realizados por el Grupo IT arrojan que el mayor peso (un 70 %) en este parque lo ocupan las locomotoras diesel de pequeña potencia (menos de 1000 hp), mientras que el nivel de disponibilidad técnica total del parque apenas supera el 45 %.

Como resultado de estos estudios se propuso como solución alternativa, la introducción de locomotoras a vapor modernas con potencias de 800 hp que se utilizarían para tarccionar trenes de carga ligeros, pasaje y trabajos de maniobra. Según análisis realizados a posteriori, la factibilidad de emplear este tipo de máquina ante una insatisfecha y creciente demanda de tráfico, requerirá incorporar para el año 2007 una 36 a 38 locomotoras de vapor modernas con el fin de sustituir similar cantidad de diesel en explotación con potencias equivalentes.

La introducción de estas nuevas unidades de vapor modernas estará en función de la factibilidad real de fabricación de estos equipos bien en el país o en el extranjero y la creación de condiciones de explotación requeridas. Estos aspectos están siendo estudiados por el Proyecto Prometeo en el marco del cual se ha realizado ya el proyecto técnico de una locomotora energéticamente autosustentable totalmente nueva, la denominada LVM 800.

Paralelamente se han realizado estudios sobre la fabricabilidad de esta máquina. Según evaluaciones de la industria sideromecánica cubana y expertos extranjeros, el país cuenta con la capacidad tecnológica y de proyectos para completar el diseño general incluyendo el sistema de combustión, los planos de taller y organizar la producción en Cuba de este tipo de máquina. El Proyecto apunta a introducir un prototipo de locomotora aún mas atractiva, que estará mejor adaptada a las condiciones locales de atención y con bajos costos de mantenimiento y operación.

La máquina está concebida como una locomotora térmica alimentada con biomasa. Tal tecnología no existe en el mercado. El diseño será tan simple, de modo que se pueda darlo en licencia a tantas industrias y países como sea posible. Será de fabricación soldada sin que medie ningún componente importante fabricado en acero fundido. La tecnología de avanzada descansa en principios bien desarrollados, como son algunos por ejemplo:

- mas altas presiones y temperaturas del vapor,
- un tiraje de mayor eficiencia energética,
- pre-calentamiento del agua y del aire con vapor de escape,
- aplicación de la combustión por gasificación,
- tratamiento de agua de avanzada excluye la corrosión,

– gracias a una mejor adherencia se puede contar con fuertes esfuerzos de tracción.

Como resultados aún en proceso, en 1997 se realizaron conversaciones con expertos suizos de la fábrica SLM, especialistas alemanes y norteamericanos interesados en esta tecnología. En estos momentos el Proyecto está en fase de búsqueda de financiamiento y evaluación de los costos de producción en plantas cubanas o extranjeras.

4.2. Experiencias cubanas en la modernización de una locomotora de vapor. (la ALCO 2-8-0 No. 1816).

La modernización de locomotoras de vapor ha sido definida como la aplicación parcial de los principios que se ejecutan en el diseño de locomotoras nuevas a las locomotoras existentes, sin introducir alteraciones estructurales y conservándose los componentes principales.

Esta aplicación se extiende en una amplia gama que comprende no solo a los distintos elementos de la locomotora sino a la teoría que la inspira como máquina termodinámica de transformaciones de energía, así como a los principios de operación y mantenimiento.

Los objetivos pueden ser muy variados si el proyecto se encara de modo general o muy específicos si se trata de alcanzar uno en particular. También puede presentarse de forma ¨pasiva¨, es decir, ver que se puede hacer con una determinada locomotora dentro de un marco dado de circunstancias de presupuesto tales como, tiempo, facilidades industriales, perspectivas de futuro, panorama energético, costos de tracción etc. Estos objetivos son los que se han perseguido con la modernización de la No. 1816.

5. Características de la locomotora 1816.

La locomotora No. 1816 es un tipo de máquina ”Consolidation” 2-8-0, con dos cilindros de 20” X 26” (508 mm X 660 mm); ruedas de 50” (1270 mm) de construcción norteamericana por la ALCO en el año de 1919 para trocha de 1435 mm. El esfuerzo nominal de tracción para una presión de 180 lb/plg^2 es de 14432 kgf lo que supone un peso adherente de aprox. 60 Tf.

Su caldera es tipo Straight Top (envolvente redonda) con un Ø de 64” (1,63 m). Tiene 21 elementos sobrecalentadores (128/136; 31/38), los tubos chicos son de 2” (46/51). El área de la placa tubular destinada a los tubos grandes es menor de la mitad del total lo que indica una baja temperatura de vapor, menor de 330 º C. La alimentación de agua caliente se hace a través de una bomba reciprocante y un intercambiador, o por inyector de carga. Los cilindros, conforme a los diseños de fábrica estaban muy mal aislados, la potencia máxima recién reparada es de aprox. 1440 hp y la máxima velocidad de diseño es de 80 km/h.

5.1. Modernización de la caldera.

Producto del estado técnico que presentaba la caldera original, se le realizaron trabajos de reparación de envergadura, utilizándose para ello diversas técnicas de soldadura, por lo que fue necesario efectuar un riguroso control de calidad de los trabajos de reparación de dicha caldera consistentes en:

– reparación por soldadura del cañón de la caldera,

– verificación del estado de los remaches de la caldera.

Los principales trabajos de modernización a la caldera consistieron en:

– Se construyeron placas tubulares nuevas, aumentándose la cantidad de elementos sobrecalentadores.

– Se construyó un eyector de tiro LEMPOR con lo que se disminuyó la contrapresión de escape.

– Raspado exterior y pintura anticorrosiva de la chapa exterior de la caldera.

- Reemplazo del conjunto de stays originales por otros tipo TROSS articulados.
- Aislamiento con lana de vidrio del cañón y el fogón de la caldera.
- Aplicación de la combustión por gasificación, (inyección de vapor de escape al aire primario, dos puertas para el hogar tipo guillotina, toberas de aire secundario).
- Fijación de la máxima presión de trabajo de la caldera; inspección de espesores; muestras de material, cálculos, regulación de válvulas de seguridad, prueba hidráulica.
- Construcción y montaje de la bomba de agua alternativa para alimentación de agua caliente a la caldera.

5.2. Modernización de la parte motriz de la máquina.

Como principales elementos modernizados en la parte motriz se relacionan los siguientes:

- Aislación ”exagerada” de los cilindros de vapor empleando lana de vidrio con el objeto de disminuir al máximo posible las pérdidas de vapor por transferencia térmica al medio ambiente.
- Válvulas cilíndricas nuevas con 16 aros, lo que mejora substancialmente su efectividad, al elevar su hermeticidad interna.
- Camisas de válvulas de distribución nuevas con diseño avanzado.
- Embolo (pistón principal) nuevos con mayor cantidad de aros y de menor espesor para lograr mayor hermeticidad interna.
- Rectificación de cilindros, redondeo de bordes filosos que afectan el flujo de vapor (mejora del aerodinamismo interno).
- Nuevo sistema de prensaestopas Paxton - Mitchell para el vástago del pistón principal, contravástago y compresor de aire, lo que reduce substancialmente las fugas de vapor por dichos elementos reciprocantes.
- Instalación de un compresor de aire adicional accionado directamente desde el mecanismo de distribución (disminuye el gasto de vapor del compresor principal y aumenta la capacidad de aire comprimido para el servicio de los trenes).
- Lubricación del mecanismo y las cajas de mechas y almohadillas, tuberías plásticas, aceite de cilindro, etc, para aumentar su autonomía en 2000 km sin habilitación.
- Revisión del equilibrado de las masas alternativas de la locomotora.
- Modificación del sistema de lubricación de los cilindros acorde con los requerimientos de trabajo del vapor sobrecalentado.
- Instalación de una bomba de pre-calentamiento de agua.

5.3. Modernización de la cabina.

Se introdujeron mejoras en las condiciones de trabajo del maquinista y del auxiliar dadas por un rediseño de la cabina. La más importante se logró al hacerla lo menos calurosa posible:

- Sacando al exterior todas las tuberías de escape.
- Aislando de madera el techo y paredes.
- Sustituyendo los grifos de prueba por un nivel.
- Replanteándose el diseño de la escalerilla y el pasamanos.

5.4. Modernización del alijo o tender.

Se aumentó la capacidad de combustible levantando con chapa soldada los laterales, frente, trasero, etc. La toma de agua consiste en un bolsillo que sale hacia afuera para recibir el chorro de habilitamiento. Se cambiaron los bogies por otros de mejor diseño (del tipo Sumitomo, japonés). Se colocaron mamparas ó rompeolas en el tanque de agua.

5.5. Tratamiento interno de agua para la locomotora modernizada.

La posibilidad de modernizar la locomotora de vapor 1816 para alcanzar una eficiencia energética superior (locomotora de 2da Generación) elevando la potencia de 1200 a 2000 hp, sustituyendo el diseño empírico por la termodinámica y empleando aros adicionales para reducir la pérdida de vapor por los cilindros además de otros adelantos tecnológicos, implican exigencias en el tratamiento de agua. Si en una locomotora de 1ra Generación(las que posee actualmente el ferrocarril azucarero) los fenómenos de formación de espuma, depósitos de sales insolubles (incrustaciones) y corrosión son perjudiciales, en las locomotoras de 2da Generación son inadmisibles. Es por esto que el tratamiento de agua debe ser riguroso de modo que no se produzcan ninguno de los efectos mencionados anteriormente.

En esta locomotora se utiliza un tratamiento de agua interno (en el alijo) que es un método de fácil aplicación y ajustable a cualquier calidad de agua a diferencia de otros que dependen de la calidad del agua de abasto.

Esta tecnología no es nueva, existe experiencia de su aplicación en los ferrocarriles franceses y argentinos pero los productos empleados en ambos casos no son de fácil adquisición en nuestro país, entre otras cosas por su elevado costo.

Fue por tanto necesario sustituir parte de los productos por otros nacionales de fácil obtención, así como variar la tecnología de obtención de otros de acuerdo a las condiciones de equipamiento de nuestros laboratorios.

Se diseñó una tecnología para el tratamiento de agua con una alta integración de productos nacionales y de fácil obtención en las condiciones de un laboratorio de control de los que posee la Unión de Ferrocarriles así como los ensayos de explotación en condiciones de zafra en un CAI.

Para lograr este objetivo fue necesario la síntesis de un compuesto antiespumante PA-1 a escala de laboratorio, la sustitución del inhibidor de corrosión, de importación, por uno nacional de iguales características, la fabricación del ¨Producto Unico¨ su puesta a punto en locomotoras de un CAI, y el análisis periódico de los parámetros del agua y de la formación de espuma) para la evaluación posterior de la efectividad del tratamiento.

La 1816 continúa con un riguroso Esquema de Pruebas donde una vez completada la instalación de la bomba de agua caliente, se procederá a medir los efectos de los cambios y nuevas tecnologías introducidas y el grado de incremento de su eficiencia.

6. Conclusiones.

El proyecto de modernización desarrollado presenta una locomotora reparada a bajo costo por capital invertido en su proceso (~ 30 mil US $), capaz de utilizar tanto petróleo como biomasa local como combustible, la cual requiere de un mínimo de atención y mantenimiento.

Generalmente las alternativas que se ofrecen en el mercado internacional para los países en desarrollo resultan ser solamente máquinas de alta tecnología de corte occidental las que no pueden ser soportadas financieramente por la mayoría de nuestros países.

Este proyecto que actualmente promueve Cuba, concibe materializar la ingeniería de la nueva tracción a vapor para el siglo XXI, mostrando la viabilidad de utilizar locomotoras sostenibles capaces de hacer frente a los inconvenientes de la locomotora diesel cada vez mas sofisticada, con particular atención a las condiciones que se dan en los países en desarrollo.

A fin de alcanzar esta meta, no se hace necesario desarrollar ninguna tecnología costosa. Es posible combinar sistemas bien probados que datan de mas de un siglo con el inventario tecnológico de los tiempos que corren.

- Adoptar como política estatal la conservación y perfeccionamiento tecnológico de las locomotoras de vapor existentes en los países que cuentan con estas.
- Organizar la preparación para el desarrollo de la tracción a vapor en los politécnicos y escuelas técnicas adecuados con la cooperación del personal calificado en vapor de los talleres cercanos o de asociaciones, instituciones, etc que promuevan el nuevo vapor.
- Organizar seminarios técnicos, talleres y encuentros para diseminar el conocimiento de la tecnología moderna en la tracción a vapor entre directivos del transporte ferroviario, profesores, investigadores, proyectistas y técnicos en general.
- Generalizar el uso de la tecnología de tratamiento de agua para calderas empleada en las experiencias cubanas a diferentes grupos de locomotoras de vapor.
- Introducir en los trabajos de reparaciones mayores de locomotoras de vapor que se realicen algunas de las innovaciones desarrolladas por el proyecto cubano (Prometeo), mediante la adecuación de proyectos y la posible asesoría de los especialistas del Grupo IT (promotor del proyecto).
- La tracción a vapor juega un papel decisivo en la producción azucarera cubana, según experiencias obtenidas, sus costos de operación son inferiores a los de la tracción diesel, y hay nuevos elementos que permiten no solo conservarla, sino hacerla mas efectiva.
- La modalidad de empleo de locomotoras a vapor para servicios turísticos resulta una alternativa sumamente ventajosa para nuestro país dadas las potencialidades de que dispone el Sistema Nacional de Transporte con su infraestructura creada, pero aún mas por ser este el único país del mundo donde existe un verdadero museo viviente de locomotoras de vapor de principio de siglo y un buen número de instalaciones ferroviarias y entornos que se vinculan con la época o resultan pintorescos.
- Promover esta modalidad en Cuba con locomotoras ecológicamente neutras se transforma en un aporte a la protección ambiental y una contribución a la política de nuestro país para un desarrollo turístico compatible con la calidad ambiental.

La locomotora de vapor no ha desaparecido aún en los umbrales del siglo XXI. Resurge como el Ave Fénix sobre conceptos y tecnologías novedosas ofreciendo amplias potencialidades para el desarrollo sostenible de nuestros países y contribuyendo a la protección medioambiental de la humanidad.

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Locomotora No. 1816, construida en 1919, modernizada en Cuba en 1997.

Foto 1

Foto 2

Locomotora a Vapor Moderna LVM 800 (segunda generación) de 800 hp con 15000 kg de esfuerzo tractivo en el arranque, para velocidad máxima de 50 kph.

Apta para trochas desde 981 a 1676 mm y radio mínimo de curvas de 70 m. Tara de 30 tf balastada fuertemente con combustible y agua.

Proyecto que desarrolla Cuba para el vapor moderno del Siglo XXI.

3 - Modern Steam in Revenue Service

Roger Waller, Dipl. Ing. ETH

Abstract:

After an interval of 40 years the Swiss Locomotive- and Machine Works in Winterthur started to build new steam locomotives again. In 1992 three prototypes of an entirely new developed rack steam locomotive entered commercial service. In 1996 five identical production locomotives followed. Taking the Brienz Rothorn Railway as an example, this paper explains the way this at a first glance rather unconventional solution came to be. It also gives an idea what kind of innovations were necessary to bring the seemingly old-fashioned technology up to today's standards and make modern steam a commercially viable option. The aim was not to be just better than the old steam locomotives, but to be competitive against today's Diesels, which were about to eliminate steam operation. We can indeed claim that thanks to the modern steam locomotives, the ongoing dieselisation on both the Brienz Rothorn and the Schafberg line was stopped, more so even reversed, in that the percentage of steam operation has steadily increased since the arrival of the modern steam locomotives.

At the time a German standard gauge steam locomotive is being modernized in Winterthur along the lines of the modern steam technology implied on the rack tanks. The locomotive is destined mainly to pull the famous Orient-Express trains. It will prove that the modern steam technology can also be used for larger locomotives.

So far rationalizing a steam operated railway inevitably meant dieselisation or even electrification. In both cases the result is a considerable loss of attractiveness. Now modern steam locomotives offer an economical and ecological operation without the loss of attractiveness and we now can claim that modern steam is proven technology.

Diesels on the Brienzer Rothorn

Although a mere 99% of all railways in Switzerland are electrified, there is one remarkable exception, the Brienz Rothorn Railway. Electrification was discussed more than once but always considered too expensive. So the railway remained 100% steam operated until 1972. Up to then the rolling stock consisted of 5 steam locomotives built in 1891/92 and two more powerful ones built in 1933/36. The older locomotives push one coach seating 48 passengers, the newer ones transport up to 80 passengers in two coaches. Each train requires a staff of three (driver, fireman and guard). Due to the limited capacity of its trains the railway was unable to cope with the demand, especially on sunny days. Various solutions to increase the capacity and to reduce operating costs have been discussed. A report *on these findings stated, that new steam locomotives would provide the most attractive solution. Unfortunately, at that time, no locomotive builder was prepared to offer them. The "second best" option was chosen: new diesel locomotives. The prototype, the Hm 2/2 No. 8 was not a real success, but nevertheless demonstrated what could be done. The locomotive entered service in 1973 and was allowed to push one coach only. But there was no fireman and short preparation times. Based on this prototype, two much improved Hm 2/2 (No. 9 and 10) were built and entered service in 1975. Pushing two lightweight coaches with up to 112 passengers and requiring a staff of only two per train, their economy was far superior to the one of the old steam locomotives. On top of their economy No. 9 and 10 were, unlike the prototype No. 8, quite reliable in service. Is it astonishing that the railway took full advantage of the diesels? When there was heavy traffic, diesel was used because steam was unable to cope with the demand. When traffic was low, diesel was used because steam was too expensive. Steam remained useful though, mainly for advertisement, less so for actual train service. The result of this traction policy was, that the majority of passengers were transported by diesel, whether they liked it or not. When the railway announced their intention to buy a fourth diesel, I wrote a letter to the director pointing out the fact that already most passengers had no choice but to take a diesel train. Yet another diesel would make matters even worse and relegate steam definitely to advertisement purposes. I did not only complain though but proposed what I felt was a much better solution: a new, modern steam locomotive with an economy comparable to diesel, but much more attractive. Unfortunately, my proposal came too late to prevent No. 11, put in service in 1987. But it created interest and later turned out to be the start for modern steam locomotives. Table 1 shows the motive power of the Brienz Rothorn Railway in 1990, before the introduction of modern steam locomotives.

The Shortcomings of old Steam Locomotives

Promising a modern steam locomotive that would be economically competitive against (modern) diesel was one thing, realizing it another. First a list of disadvantages of the traditional steam locomotives was produced:

- **Higher staff costs**: mainly due to the need for a fireman, but also because of longer hours for servicing and supervising the steam locomotives
- **Higher maintenance costs**: mainly due to the old age of design and material
- **Low thermal efficiency**: due to a generally low cycle efficiency but also due to various deficiencies in design and calculation
- **High stand-by losses**: steam locomotive boilers usually were not or only insufficiently insulated resulting in considerable radiation losses
- **Longer preparation times**: whilst diesel- and electric locomotives can (almost) be put in service by "pushing a button", traditional steam locomotives needed careful nursing before and after each trip, especially when coal-fired.
- **Environmental nuisance**: traditional steam locomotives are increasingly criticised for their environmental impact. Visible air pollution and dripping oil are not to everyone's liking. This is not helped by some rail fans, which not only ignore it but also contribute to strengthen the bad image by ordering black smoke for a "good" photograph. Thanks to the general popularity of steam locomotives, most people still tend to "overlook" these negative aspects, but I'm sure it will no longer be tolerated on tourist lines with regular steam trains.

The above is by no means a complete list of the shortcomings of the traditional steam locomotives but reflects the main reasons why most railways were dieselised or electrified. If we wanted to reverse that process on at least some of the railways, we would have to rectify the above deficiencies of the steam locomotive. Much brainstorming was necessary but out came a proposal, which should do the job. The appearance of the locomotive was not much different from the older ones, which seems to be an advantage rather than a disadvantage, at least on tourist lines.

New Steam Locomotives: a Dream Comes True

The proposal, including a first design drawing, was presented to the director of the Brienz Rothorn Railway in 1987. The following advantages were claimed for the new locomotives:

- **One man operation:** the new steam locomotives do not need a fireman, thus bringing staff costs of steam to the same level as for diesel or electric traction
- **Light-oil-firing**: thanks to a modern oil-firing system, the problem of air pollution would be solved. The oil-firing would also eliminate problems like line-side fires, fire cleaning, clinkering, ash disposal and additional working hours
- **Fully insulated boiler and cylinder**: to reduce stand-by losses and to improve the efficiency, insulation quality of stationary boilers was envisaged. Good insulation not only saves energy, it is also

essential to keep an engine in steam overnight unattended. If there is still steam pressure in the boiler, the oil firing can immediately be turned on (almost by "pushing a button").

- **Streamlined steam passages**: the BRB locomotives No. 6 and 7 have their cylinders in the middle underneath the boiler and the gear in front underneath the smoke box. This arrangement was to be reversed for the new locomotives by placing the cylinder underneath the smoke box to give better streamlining of steam and exhaust pipes. The steam passages inside the cylinder were to be improved too.
- **Roller bearings**: One of the main expenditures for the maintenance of traditional steam locomotives is related to plain bearings. Replacing these by correctly designed, sealed roller bearings would save a lot of servicing and maintenance. No oil would be lost, making new steam locomotives environmentally friendly also in this respect.
- **Interchangeable parts**: traditional steam locomotives used to be different even if built to the same drawings, which made it difficult to have spare parts on stock. Today's philosophy requires interchangeable parts to ensure that the engines are back in service as soon as possible. Thanks to todays CNC manufacturing methods, the interchangeability of parts on new locomotives is not much of a headache.
- **Electric preheating device**: with the electric preheating device a cold boiler can be put in steam overnight or be kept at any desired temperature, in both cases without supervision. (A more detailed description of the function is given in the paper "Steam Locomotive Components for Museum and Tourist Railways".)

With this information on the proposed new steam locomotives, enough interest was created to obtain a request for an offer. Now convincing SLM to actually offer these new steam locomotives was real hard work. In the end it was decided to do a market survey to see if there is enough potential for more than one new steam rack locomotive. SLM decided that at least six locomotives would have to be ordered otherwise the proposal was dead. The result was quite astonishing and showed a potential for no less than 15 new locomotives. Main customer would be the Austrian Federal Railway, which asked for 12 locomotives for their two rack lines on the Schafberg and the Schneeberg. Now the risk of building 15 locomotives to an entirely new design, restarting after an interval of 40 years with a team that has never built a new steam locomotive before seemed too high a risk for SLM. Subsequently it was decided to build a prototype. The negotiations with possible customers resulted in three orders for prototype locomotives, one each for Brienz Rothorn Railway, Montreux - Glion - Rochers-de-Naye (both in Switzerland) and Austrian Federal Railway.

All three new locomotives have been thoroughly tested in SLM before delivery. In 1992 all were commissioned and entered commercial service soon afterwards. The good experience gained with these locomotives in daily service lead to an order of five production locomotives, virtually to the same design. A few details have been modified of course following the experience in revenue service, but otherwise the basic design features remained unchanged. Table 2 shows the rolling stock of the Brienz Rothorn Railway in 1996 with now three new locomotives, No. 12, 14 and 15. No. 13 was painted on a mock-up of the cab and is not used for a locomotive. The prototype diesel no. 8 was sold. Table 3 shows the development of mileages done by each locomotive since the introduction of the new steam locomotives. It can clearly be seen that the new steam locomotives took away kilometres not only from the old steam locomotives but mainly from the diesels. Whilst from 1973 to 1992 there was a strong tendency to diesel, this trend was reversed by the new steam locomotives.

We can indeed claim that thanks to the modern steam locomotives, the ongoing dieselisation on both the Brienz Rothorn and the Schafberg line was stopped, more so even reversed in that the percentage of steam has steadily increased since the modern steam locomotives began to operate.

* BRIENZ ROTHORN-BAHN: Erneuerung des Rollmaterials, November 1975, unpublished

Rolling Stock of the Brienz-Rothorn Railway 1990						
Engine No.	**Type**	**built**	**Coaches**	**Capacity**	**Crew**	**Productivity**
1.....5	Old Steam	1891/92	1	48	3	100%
6 + 7	Old Steam	1933/36	2	80	3	167%
8	Diesel	1973	1	48	2	150%
9 + 10	Diesel	1975	2	112	2	350%
11	Diesel	1987	2	112	2	350%

Remarks: *Capacity*: Number of passengers per train
Crew per Train: Driver, (Fireman), Conductor
Productivity: Number of passengers per train crew member as compared to old steam of 1891/92

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Table 1

Rolling Stock of the Brienz Rothorn Railway 1997						
Engine No.	Type	built	Coaches	Capacity	Crew	Productivity
1.....5	Old Steam	1891/92	1	48	3	100%
6 + 7	Old Steam	1933/36	2	80	3	167%
9 + 10	Diesel	1975	2	112	2	350%
11	Diesel	1987	2	112	2	350%
12	New Steam	1992	2	120	2	375%
14 + 15	New Steam	1996	2	120	2	375%

Remarks: *Capacity:* Number of passengers per train
Crew: Driver, (Fireman), Conductor
Productivity: Number of passengers per train crew member as compared to old steam of 1891/92

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Table 2

Engine Performance on the Brienz Rothorn Railway 1992-99 (km)										
Engine	**Type**	**built**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
1	Old Steam	1891	2606	1056	1458	158	468	1250	568	0
2	Old Steam	1891	1641	1916	2161	2030	1834	1607	1598	1873
3	Old Steam	1892	2084	1292	0	0	0	0	0	0
4	Old Steam	1892	0	0	0	0	0	0	0	0
5	Old Steam	1891	2387	0	1208	1850	0	0	962	1309
6	Old Steam	1933	3346	2304	3088	2604	1972	2541	2204	2643
7	Old Steam	1936	3560	2672	3221	2618	1992	2160	2162	2648
8	Diesel	1973	2421	688	1232	1150				
9	Diesel	1975	6100	4586	5450	3453	3621	3124	2172	1213
10	Diesel	1975	6263	4135	4138	3948	2438	2758	2679	2579
11	Diesel	1987	6923	5501	5188	5691	3929	5018	5341	4938
12	New Steam	1992	1675	4609	5637	5513	3969	4762	4058	5319
14	New Steam	1996					4033	4101	4182	4638
15	New Steam	1996					4386	4488	3980	5184
% Steam Traction			44%	48%	51%	51%	65%	66%	66%	73%
% New Steam Traction			4%	16%	17%	19%	43%	42%	41%	47%

Remarks: Engine No.8 is a prototype Diesel locomotive; it pushes only one coach; it was sold in 1996
Engine No.12 is a prototype steam locomotive, commissioned 28 / 07 / 1992; 1992 was not a full season for her

BRB1Da.xls / R. Waller / 16.12.99

Table 3 (updated)

4 - Modern Steam Traction and the Protection of the Environment

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After a break of 40 years, Swiss Locomotive and Machine Works (SLM) in Winterthur (Switzerland) resumed building modern steam locomotives. In 1992, three prototype rack tank locomotives were delivered to the Austrian Federal Railways (ÖBB), the Brienz-Rothorn-Railway (BRB) and the Montreux-Glion-Rochers-de-Naye Railway (MGN), the latter two in Switzerland. New steam locomotives should, like any new technical equipment, be optimized for both minimum operating and maintenance costs and lowest possible pollution. The paper describes the design considerations to meet these requirements and presents the results of emission measurements which show that the new oil-firing system specially developed for these modern steam locomotives causes much lower emissions of CO and NO_x *than the competing diesel traction. The experience gained in regular service shows that most of the disadvantages of traditional steam locomotives have been eliminated. The overall economy of steam traction has been drastically improved. The good performance, high availability, low maintenance costs and low pollution of the new steam locomotives and their popularity with the travelling public led to orders for five series locomotives that entered service in 1996.*

1 What circumstances led to orders for new high-tech steam locomotives?

Tourist railways and railways with a high percentage of tourists among their passengers need steam locomotives because they attract the public more than any other form of motive power. Steam locomotives mean more passengers and thus more revenue. On the other hand, old steam locomotives are rather expensive to run because of high staff and maintenance costs, relatively low thermal efficiency and high stand-by losses. Due to the difference in age and thus in levels of technological development, new diesel locomotives or railcars usually have lower operating costs than old steam locomotives – but they do not attract passengers. Representative opinion polls in Austria revealed that 79 % of tourists prefer steam locomotives, 3 % prefer diesel traction and 18 % have no preference [1]. In fact, drops in ticket sales after dieselization can easily outweigh the lower operating costs achieved, even more so because capital costs entailed by dieselization are not negligible (electrification entails even higher capital costs and does not attract tourists either). Heavy deficits rather than the expected profits are the result. New modern steam locomotives both attract passengers and offer substantial savings in operating and maintenance costs. They are therefore the **only** solution to the problem of long-term profitable commercial tourist railway operation.

The main advantages of modern steam power are:

- one-man operation
- extremely environment-friendly oil-firing system
- fully insulated boiler and cylinders
- high thermal efficiency
- roller bearings and central lubrication
- external electric preheater for unattended steaming-up
- high availability (the same as diesel locomotives)

So far, the Austrian Federal Railways (ÖBB), the Brienz-Rothorn-Railway (BRB) and the Montreux-Glion-Rochers-de-Naye Railway (MGN) have fully realized these advantages of modern steam power for tourist train operation. In 1988, these railways ordered one prototype each of a new H 2/3-type (rack tank 0-4-2) high-tech steam locomotive from Swiss Locomotive and Machine Works (SLM). SLM had built its "last" steam locomotives back in 1952 but had resumed locomotive boiler construction in 1986. Both the railways and the SLM management were convinced that new high-tech steam locomotives were a viable and economically reasonable option for all parties involved.

Table 1: Comparison between old and new steam locomotives of the Brienz-Rothorn-Railway (BRB)

Type	H 2/3	H 2/3	Improvement
Engine No.	6; 7	12; 14, 15	
Year built	1933; 1936	1992; 1996	
Weight in service	20 t	15 t	- 25 %
Power	220 kW_i	300 kW_i	+ 36 %
Power to weight ratio	11 kW/t	20 kW/t	+ 82 %
Fuel consumption per train trip	11550 MJ	6830 MJ	- 41 %
Fuel consumption per passenger trip	145 MJ	57 MJ	- 61 %
Maximum speed 1 in 4-gradient	9 km/h	14 km/h	+ 56 %

2 General concept of the new, modern steam locomotives

Oil-firing was chosen with one-man operation and low day-to-day maintenance costs in mind. Old oil-fired steam locomotives burnt heavy fuel oil (bunker C), but this was ruled out for the new engines. Due to its high sulphur content (≥ 1 % by weight), heavy fuel oil is detrimental to both environment and boiler life (corrosion). Moreover, heavy fuel oil requires heating for both handling and the actual firing which means more dead weight on the locomotive (heating coils) and additional use of energy. As heavy fuel oil is used only by big factories and power stations, it is difficult to obtain in smaller quantities and not readily available in tourist areas, whereas there is a good distribution network for extra-light (EL) oil used in domestic central heating. Due to its low sulphur content (0.10-0.20 % by weight; qualities with an even lower sulphur content are becoming available), its high heat content (lower calorific value ≥ 42.5 MJ/kg) and its cleanness it is one of the least air-polluting locomotive fuels.

In order to achieve good combustion in the small firebox, a new oil-firing system had to be developed because the maximum possible length of the flame path was not sufficient for a traditional single burner concept with its one big flame guided in the shape of a C or an S. In order to shorten the flame-length, four smaller main burners with a maximum flow rate of 75 l/h each (= approx. 750 kW of heating power per burner) were fitted in the square bottom of the firebox. In their center, there is a so-called pilot-burner (with a maximum flow rate of 8 l/h = approx. 80 kW of heating power) that is used to ignite the main burners and to steam up the locomotive after a night's rest. The total burner power is thus 3.08 MW. All burners are of the specially developed "injection burner" type. Their flames are directed vertically upwards and do not touch the firebox walls. Therefore the traditional brick lining is not necessary, which means better and quicker heat transfer and undisturbed combustion leading to higher boiler efficiency, better response to load changes and much lower air pollution. The injection burners atomize the oil by means of whirling steam that has passed a special superheater coil adjacent to the pilot-burner. Oil flow and thus firing rate are controlled by means of a compound-regulator. This device can be controlled with one hand and ensures the correct atomizing steam pressure for any oil flow rate chosen.

Instead of the fusible plugs used on coal-fired steam locomotives, a low water detector shuts off the main burners automatically via an electromagnetic valve if the water level falls below the safety margin above the firebox crown.

In order to reduce thermal losses drastically, both boiler and cylinders are very well insulated. A roll shutter is fitted to shut off the air flow to the firebox completely when all burners are turned off. When going downhill, the Riggenbach counter-pressure brake is used, all burners are turned off, and the roll shutter is closed – fuel consumption is thus nil.

Due to the excellent boiler insulation and the roll shutter, a locomotive stabled fireless in the evening at almost full boiler pressure will still have a pressure of 800 to 1000 kPa left in the boiler the next morning. It takes the pilot-burner only about 38 minutes to steam up the locomotive from 800 to 1600 kPa, and the natural draught of the chimney is sufficient for low-emission combustion. If the blower and the main burners are used, pressure can be built up much more quickly, of course. The electric preheater is therefore only necessary for unattended steaming-up of a dead engine or if the locomotive is to be kept in steam for continuous stand-by. If electric preheating is not available and the locomotive is dead, the pilot-burner can also work with externally supplied compressed air.

The classical two-cylinder steam engine with Walschaerts valve gear (or Heusinger gear as it is called in Germany and the countries influenced by German locomotive practice) incorporates all known improvements such as

- enlarged steam chest volume
- straight steam ports
- minimum clearance volumes
- efficient exhaust system (a simplified LemPor-exhaust is fitted)
- generous valve travel
- good cylinder insulation

The locomotive has a feedwater heater of the closed type, and the superheater is designed to achieve a steam temperature of 420°C.

3 Environmental protection: modern steam versus modern diesel

As far as air pollution is concerned, is a fair and realistic comparison between modern steam and modern diesel traction possible? On the BRB, the new H 2/3-type steam locomotive No 12 and the Hm 2/2-type hydrostatic diesel locomotives Nos 9-11 are direct competitors (the prototype hydrostatic diesel locomotive No 8 of 1973 is not considered here). Both the diesel locomotives and the new steam locomotive cannot make full use of their rated power because they have to work in the same diagram as the old steam locomotives. To push trains uphill in the present operation, a power of about 179 kW at the driving cogwheels at a speed of approximately 9 km/h is required. In order to produce that tractive power, the new steam locomotive has to be run at a burner load of approximately 52 %, and the diesel locomotives also have to work at 52 % of their rated engine power of 485 kW. A realistic and fair direct comparison is therefore possible and makes good sense.

In order to compare the new H 2/3 steam locomotives with their diesel competitors Hm 2/2 pollutionwise, a special "mountain railway test cycle" that properly represents locomotive operation on the BRB was developed. This test cycle consists of the following three test modes (weighting factors in brackets):

1	**Stand-by**	(0.10)
	Steam:	pilot-burner only
	Diesel:	engine idling
2	**Uphill train**	(0.45)
	Steam:	179 kW at driving cogwheels
	Diesel:	179 kW at driving cogwheels
3	**Downhill train**	(0.45)
	Steam:	braking with Riggenbach counter-pressure brake, all burners turned off
	Diesel:	braking with hydrostatic transmission and engine

Table 2: Technical data of the new H 2/3 rack tank steam locomotive

Grate area		0.9	m^2
Tubes, number		62	
Tubes, dimension		38 x 2.9	mm
Flues, number		15	
Flues, dimension		114.3 x 3.6	mm
Total evaporative surface*		30	m^2
Firebox*		5.14	m^2
Tubes*		13.80	m^2
Flues*		10.92	m^2
Superheater surface*		13.23	m^2
Boiler pressure		16/18	bar
Oil firing system		Sonvico/SLM-type	
Fuel		Extra light heating oil (#2 heating oil)	
Cylinders		2	
Diameter		280	mm
Stroke		400	mm
Valve Gear		Heusinger (=Walschaerts)	
Gear ratio		2.3 : 1	
Rigid wheelbase		2070	mm
Total wheelbase		3650	mm
Rack System		Abt (Riggenbach)	
Driving cogwheels		2 x 2 (2 x 1)	
Cogs per driving wheel		15 (18)	
Length over couplers		6260	mm
Maximum width		2200	mm
Service speeds on gradients			
1 in 4		12	km/h
1 in 4.55		13	km/h
1 in 5		14	km/h
Gauge	**800**	**1000**	**mm**
Carrying wheel diameter, worn/new	637/649	693/705	mm
Pony wheel diameter, worn/new	426/440	479/493	mm
Maximum height	3200	3230	mm
Weight, empty	13000	13300	kg
Water in boiler	1200	1200	kg
Water in side tanks	1300	1300	kg
Oil (545 l, 0,86 kg/l)	470	470	kg
Weight in full working order	15970	16270	kg

* fire side

The very low weighting factor for the stand-by mode properly represents the high utilization of the Hm 2/2 diesels on the BRB, and as the new H 2/3 steam locomotives were designed to have the same availability as modern diesels (which they have proved in regular operation ever since they entered service in 1992), the same test cycle as for the diesels applied.

In diesel engine testing, CO, NO_x, HC (hydrocarbons) and particulate emissions are measured in g/kWh over certain test cycles (ECE R 49 for commercial road vehicle diesel engines, ISO F for rail traction diesel engines etc.). The pollutant mass flow rates are measured in g/h in the various test modes; at the same time, the net power obtained on the test bench at the end of the crankshaft (i.e. at the source of tractive power) is measured. The emissions over the whole test cycle are then calculated according to the formulae [2]:

$$CO = \frac{\Sigma\, CO_{\text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (1)$$

$$NO_x = \frac{\Sigma\, NO_{x\ \text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (2)$$

$$HC = \frac{\Sigma\, HC_{\text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (3)$$

$$\text{part.} = \frac{\Sigma\, \text{part.}_{\text{mass flow/h}} \times WF}{\Sigma\, P \times WF} \quad (4)$$

Steam locomotive power is most easily measured as indicated power produced in the cylinders (i.e. also at the source of tractive power). However, the losses for auxiliaries and in power transmission differ vastly between steam and diesel traction. In order to deliver a tractive power of 179.4 kW_d at the driving cogwheels (denoted by the subscript "d" meaning "at **d**riving wheels"), the new steam locomotive must produce 200.5 kW_i (subscript "i" denoting **i**ndicated power) in the cylinders whereas the diesel engine of the Hm 2/2 diesel-hydrostatic locomotive must produce 253.1 kW at the end of its crankshaft. Auxiliaries and power transmission losses add up to 10.5 % on the steam locomotive but to 29.1 % on the diesel. This must be taken into account in a fair comparison because what really counts are the emissions per kWh effectively available for traction, i.e. per kWh at the driving wheels. Therefore, P_d rather than P_i and $P_{crankshaft}$ was used in the above equations (which was applicable only for test mode 2; in test modes 1 and 3 the power output at the driving wheels was zero, of course).

Actual testing, however, is much easier if the indicated power of the steam locomotive is measured. Since the same type of diesel engine may find rather different applications, the only emission data available are those based on measurements of pollutant mass flows versus power outputs at the crankshaft. Therefore, the necessary indicated power and power at the end of the crankshaft, respectively, to obtain 179.4 kW_d were calculated from the known power consumptions of auxiliaries and power transmissions. The steam locomotive was then tested at the calculated indicated power of 200.5 kW_i; and the pollutant mass flow rates of the competing diesel engine for the calculated power of 253.1 kW could be obtained from the manufacturer.

To test the new steam locomotive, a test stand was erected at SLM. Two locomotives were placed side by side on sloped pieces of track without rack, and the crankshafts of both engines were connected via a shaft attached to the lower cogwheels of the gearboxes, from which the connecting rods had been removed. Thus the Riggenbach counter-pressure brake on one locomotive could be used to provide the necessary braking power for testing the other one under load conditions. Indicated power was measured electronically.

Two "ECOM-M/CH Smokegas-Analysis-Computers" (Stark STA-Therm, CH-2501 Biel) were used for exhaust gas measurements, one for each side of the smokebox to average out asymmetries in the combustion process introduced by the uncompensated circular whirl of the single pilot-burner. One measurement at a certain point in time then consisted of taking the average values of the readings of the two simultaneously triggered smokegas analysers. The ECOM-M/CH smokegas analyser was developed for (stationary) firing systems that burn extra light heating oil or natural gas. Exhaust gas temperature, ambient temperature, O_2-, CO- and NO-concentrations in the dried exhaust gas are measured and other data relevant for the assessment of firing systems automatically calculated. Of these, the O_2-, CO_2-, CO- and NO_x-concentrations in the exhaust gas and the air excess λ are of interest in the case of oil-fired steam locomotives. Furthermore, the device can be used to determine the "soot number" of the exhaust gas on the Ringelmann-scale (degree of blackening of a filter paper through which a defined exhaust gas volume is drawn) [3]. According to Swiss and German standardization practice, O_2- and CO_2-content of the exhaust gas are printed out in % by volume and CO- and NO_x-concentrations in mg/m^3, in both cases of the dry exhaust gas at the reference temperature and pressure of 0°C and 1013 mbar. NO_x-mass concentrations are based on the mass of NO_2 because after some time all NO is oxidized in air to form NO_2. Moreover, CO- and NO_x-concentrations may automatically be standardized on the dry exhaust gas volume (0°C, 1013 mbar) at the reference O_2-content of 3 % by volume which was done in all our measurements because in Germany and Switzerland this is the standard for comparisons of pollutant concentrations in exhaust gases from firing systems. Unfortunately, a flame ionization detector was not available so that hydrocarbon emissions could not be measured.

In test mode 1, the new steam locomotive was heated up from 800 to 1600 kPa boiler pressure within 38 minutes, using only the pilot-burner and the natural draught of the chimney. Due to the increasing firebox temperature while heating up, NO_x concentrations went up from 116 mg/m^3 at the beginning to 180 mg/m^3 at the end. The relevant average exhaust gas values over the whole 38 minutes and a total of four measurements were:

O_2	:	13.6	% by volume
CO_2	:	5.4	% by volume
CO	:	93	mg/m^3 (at 3 % O_2)
NO_x	:	149	mg/m^3 (at 3 % O_2)
λ	:	2.8	

The soot number on the Ringelmann scale was 0.

In test mode 2, first of all a stationary state had to be reached (cylinders heated up, superheat temperature and indicated power constant). This was the case after 1020 s (= 17 minutes):

Boiler pressure	=	1600	kPa
Superheat temperature	=	389	°C
Cut-off	=	32	%
Speed	=	8.9	km/h
Indicated power	=	200.5	kW_i

The average exhaust gas values over the following 723 s and a total of four measurements were:

O_2	:	9.1	% by volume
CO_2	:	8.6	% by volume
CO	:	22	mg/m^3 (at 3 % O_2)
NO_x	:	200	mg/m^3 (at 3 % O_2)
λ	:	1.8	

The soot number on the Ringelmann scale was 0-1.

Fuel efficiency η_i [4] over the whole 1743 s of testing under load in test mode 2 reached 12.7 %, specific fuel consumption was 663 g/kW_ih. Losses for auxiliaries were 1.9 kW for the feedwater pump (at 1600 kPa and 8.9 km/h) and 3.5 kW for the alternator (at 8.9 km/h); according to Giesl [5], losses in the whole steam engine of the locomotive amount to 6 %, and another 2 % are lost in the gearbox. With these values, P_d was (200.5 kW_i x 0.94 – 1.9 kW – 3.5 kW) x 0.98 = 179.4 kW_d, fuel efficiency η_d = 11,4 % [6] and the specific fuel consumption per kWh at the driving wheels 741 g/kW_dh.

In order to calculate the pollutant mass flow rates from the pollutant concentrations in the exhaust gas, the total exhaust gas volume flow rate must be known. A direct measurement on a steam locomotive is not possible, and the simultaneous measurement of fuel flow rate and air intake was impossible in this case because of the design of the air ducts in the burners. Therefore, the exhaust gas flow rate on dry basis for an O_2-content of 3 % by volume was calculated from the measured fuel flow rate and the known elemental composition (C-, H- and S-content) of the fuel derived from chemical analysis.

Table 3 shows the emission values of the new steam locomotive H 2/3 in g/kW$_i$h and g/kW$_d$h for CO, NO_x and SO_2 in the "mountain railway test cycle". The SO_2-emissions were calculated from the measured fuel flow rates and the known sulphur content of the fuel (0.15 % by weight); the values in brackets would have been obtained if the low sulphur fuel only now (1996) available (sulphur content = 0.05 % by weight) had been used.

Table 3: CO-, NO_x- and SO_2-emissions of the new H 2/3 steam locomotive in the "mountain railway test cycle"

Carbon Monoxide (CO)	Nitrogen Oxides (NO_x)	Sulphur Dioxide (SO_2)
0.19 g/kW$_i$h	1.65 g/kW$_i$h	2.01 (0.67) g/kW$_i$h
0.21 g/kW$_d$h	1.84 g/kW$_d$h	2.24 (0.75) g/kW$_d$h

For modern high-tech steam locomotives, both a 13 point emission test cycle and a test cycle corresponding to the ISO F rail traction test cycle for diesel locomotive engines were developed [7]. Unfortunately, further testing of the locomotive beyond the above experiments, which were of immediate relevance for future operation, was not possible because the railways wanted their locomotives to be delivered quickly. Delivery of the new steam locomotives took place in May and July of 1992, in the case of the BRB just in time for the 100th anniversary of the railway.

Since the beginnings of the change-over from steam to diesel traction more than 50 years ago, railways and locomotive manufacturers used to compare their new diesel locomotives with old steam locomotives that had been in service for up to 50 years. In order not to be guilty of the same unfairness the other way round, the new high-tech steam locomotive was not compared with the latest BRB diesel locomotive No 11 of 1987 but with a **fictitious** No 11 locomotive that was assumed to be equipped with a modern diesel engine. A good engine choice for this comparison was the MTU 12V 183 TD12 diesel engine, which has a rated UIC-power of 550 kW but which would be set at a rated power of 485 kW for use on the BRB diesel locomotives with their existing hydrostatic power transmission. A disadvantage even of the newest diesel locomotive No 11 is that it still burns diesel fuel going downhill (in principle, this could be eliminated).

Motoren- und Turbinen-Union Friedrichshafen (MTU) was so kind as to supply the CO and NO_x mass flow rates and fuel consumptions of their 12V 183 TD12 diesel engine for the three test modes of the "mountain railway test cycle". At a power output of 253.1 kW (necessary to obtain 179.4 kW at the driving cogwheels, test mode 2), this engine has a specific fuel consumption of 197 g/kWh which results in a fuel efficiency η_d = 30.3 %.

Fig. 1: CO-, NO_x- and SO_2-emissions, "mountain railway test cycle"

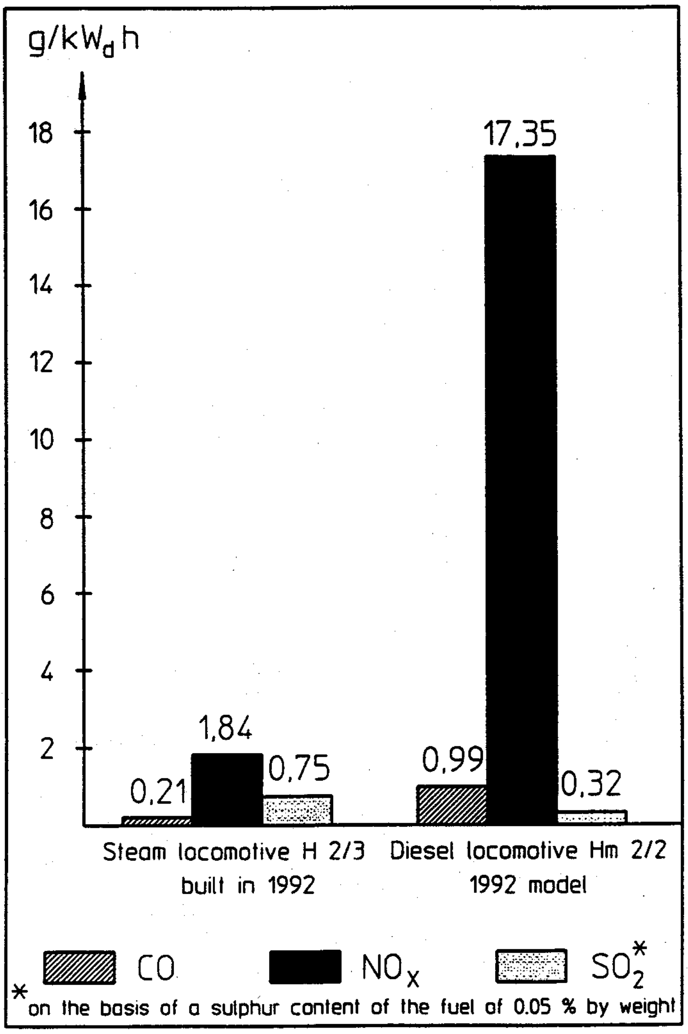

Fig. 1 directly compares the CO-, NO_x- and SO_2-emissions of the new steam locomotive H 2/3 of 1992 with those of the Hm 2/2 hydrostatic diesel locomotive No 11 if it were equipped with a modern MTU 12V 183 TD12 diesel engine also of 1992. SO_2-emissions in this graph are based on the fuels with the lowest sulphur content available in Switzerland in 1996.

Besides the noxious exhaust gases, CO_2-emissions also have to be considered. Although CO_2 is not toxic, an increase of this natural constituent of the atmosphere may lead to changes in the world climate (glasshouse effect). The CO_2-emissions of the two competing forms of motive power can be calculated from the known average carbon content of extra light heating oil (86.68 % by weight) and diesel fuel (85.92 % by weight), respectively, and the known specific fuel consumptions in the different test modes. Table 4 lists the CO_2-emissions per kW_dh in the "mountain railway test cycle" of the new high-tech steam locomotive No 12, the latest diesel locomotive No 11 as it is in service now, and the No 11 diesel if it were equipped with the modern MTU 12V 183 TD12 diesel engine.

Table 4: CO_2-emissions of the new H 2/3 steam locomotive and the BRB Hm 2/2 diesel locomotive No 11 in the "mountain railway test cycle"

Locomotive	Carbon Dioxide (CO_2)
Steam Locomotive H 2/3 No. 12 of 1992	647 g/kW$_d$h
Diesel Locomotive Hm 2/2 No. 11 MTU 8V 331 TC10	302 g/kW$_d$h
Diesel Locomotive Hm 2/2 No. 11 MTU 12V 183 TD12 of 1992	271 g/kW$_d$h

4 Conclusion

From the environmental protection point of view, it is interesting to note that – at least as far as CO and NO_x emissions are concerned – the new high-tech steam locomotive easily outclasses the competing diesel traction. Yet, the new H 2/3 is still a truly Stephensonian steam locomotive. The use of zero or extremely low sulphur heating oil poses no problem at all and would mean the elimination or drastic reduction of SO_2-emissions. In principle, LNG (liquefied natural gas) operation is also possible on new steam locomotives, which would lead to even lower overall pollution and – in contrast to the use of LNG on diesel locomotives – not lower the fuel efficiency.

The good performance, high availability, low maintenance costs and low pollution of the new high-tech steam locomotives – in addition to their popularity with passengers – led to orders for five series locomotives: in 1994, the Brienz-Rothorn-Railway ordered another two and the Austrian Federal Railways another three. These engines entered regular service during the 1996 season. The ÖBB locomotives – numbered 999.202/3/4 – are for use on the Schafberg Railway from St. Wolfgang along with their prototype sister engine 999.201.

The initial goal of the endeavours described above was to design and build an economically and ecologically competitive steam locomotive for tourist train operation. Clearly, this has been fully achieved. But even if the new steam locomotives were slightly more expensive to run than comparable diesel or electric motive power, their use would be justified because of the additional income generated by their attractiveness. The results show, however, that modern steam locomotives are fully competitive on purely economic terms.

Operating experience with new high-tech steam locomotives since 1992 has proved that modern steam traction is a serious alternative to diesel and electric motive power, not only from the ecological but also from the economic point of view. As far as economy is concerned, steam locomotives can use a wide variety of fuels, ranging from wood, peat, lignite and coal to oil, liquefied natural gas (LNG) and various new biomass fuels, whichever may be cheapest under the operating conditions in question. In Western Europe and North America oil is still the overall cheapest fuel (taking high labour costs into account), whereas coal is most economical in countries like South Africa and Zimbabwe with ample indigenous coal supplies at low prices and relatively low wages. Bearing in mind the carbon dioxide-problem (due to increasing use of fossil fuels, the CO_2-content of the atmosphere has increased which may give rise to dangerous changes in the earth's climate – greenhouse effect), regenerative, carbon dioxide-neutral biomass fuels will become important in the 21st century, and **waste** biomass fuel can play an important role in the economical operation of railways, using modern high-tech steam locomotives.

Many old diesel locomotives and diesel railcars that are approaching the end of their useful lives will have to be replaced soon, and environmental considerations call for less polluting motive power. In some cases, no doubt, electrification will be the solution but electrification requires really big investments that are justifiable only on lines with high traffic densities. Modern steam locomotives offer a low-investment solution and economical, clean and attractive service. It would be wise to consider this in future motive power decisions.

The author wishes to thank Motoren- und Turbinen-Union Friedrichshafen GmbH for supplying the MTU 12V 183 TD12 emission data.

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4. On the European continent, η_i = (indicated power over flow rate of **lower calorific value of fuel**) x 100 %. The lower calorific value of the fuel is defined as its heat content **minus the condensation heat of the water vapour formed in the combustion process**.

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

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Contents

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 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].

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

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.

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!);

- 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;

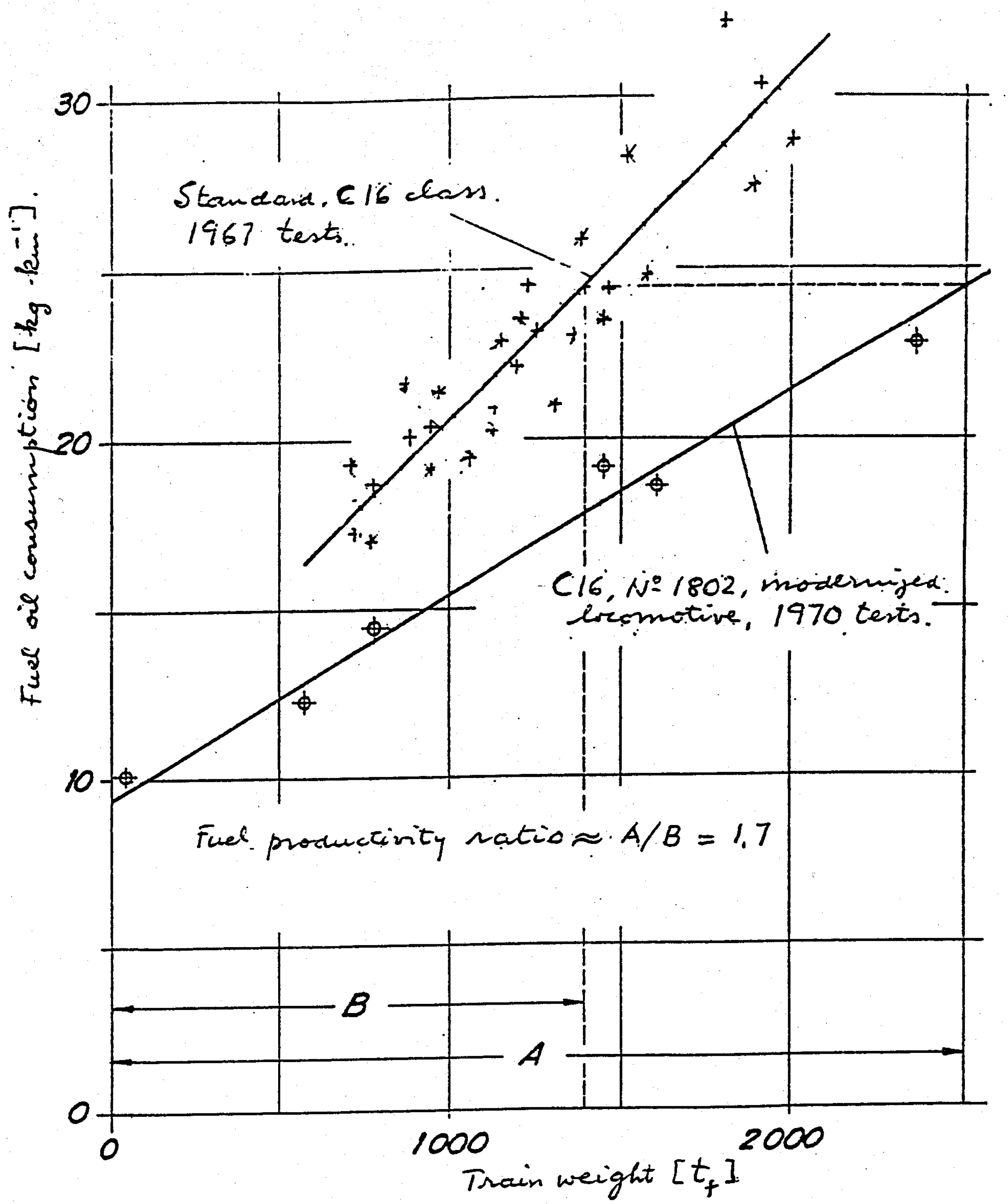

Fig. 1: Effect of a slight modernization on fuel productivity.

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;

- 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.

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.

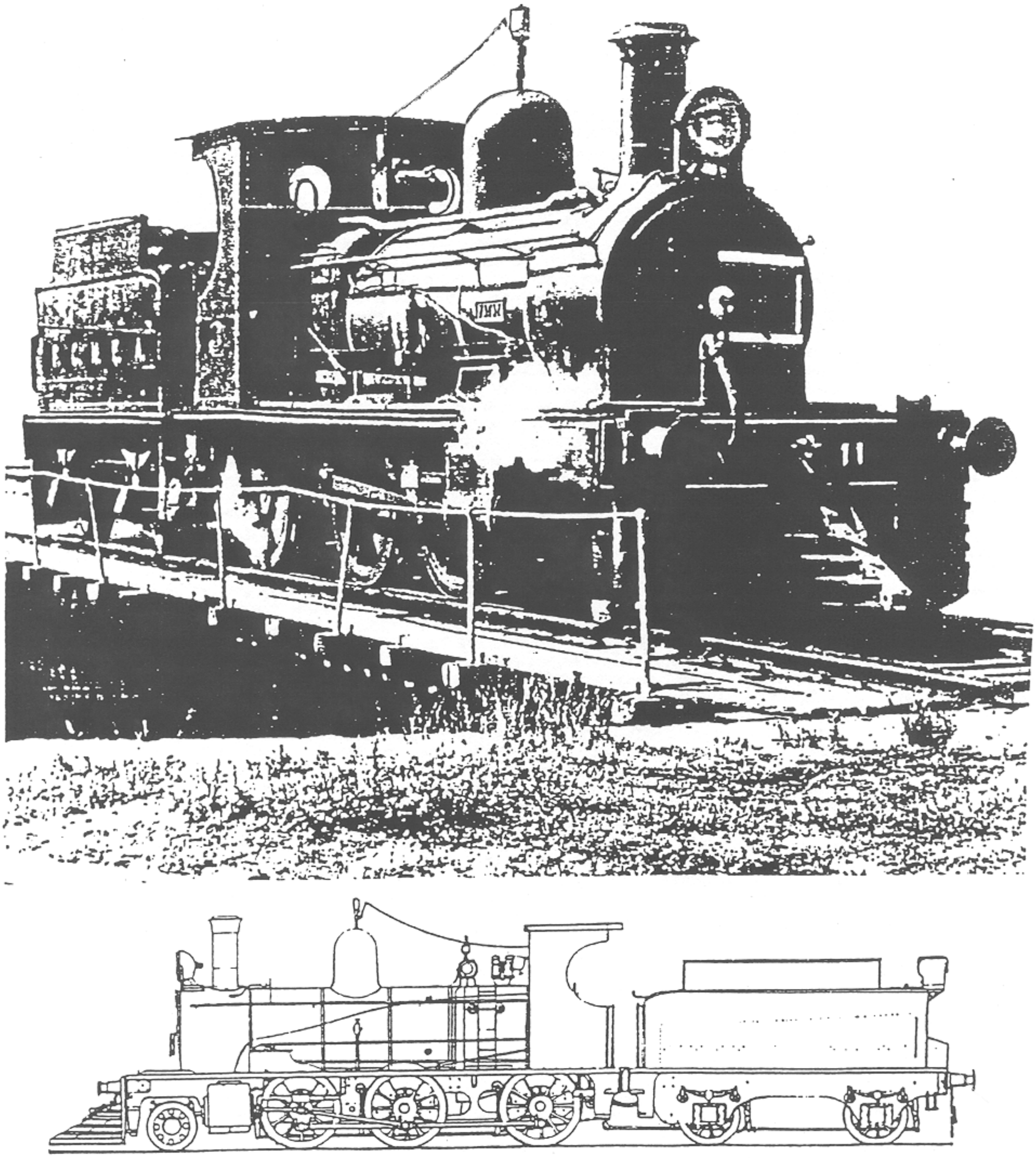

Fig. 2: NEILSON No. 11 (built in 1888), FCGU, Argentina.
Modernized by the author in 1991.

6 - Steam Locomotive Components for Museum and Tourist Railways

Roger M. Waller

Abstract: The construction of the new SLM rack tank steam locomotives was accompanied by the simultaneous development of numerous components and by-products, detailed below:

- external electric pre-heater for fireless, gentle and unattended steaming-up
- electronic measurement of the indicated power, which makes a precise and continuous monitoring of the steam engine possible
- fully welded replacement boilers
- insulation techniques to reduce heat-loss and energy consumption
- light-oil firing system for smokeless combustion even in small fireboxes
- compound-regulator for simultaneous oil/atomizing steam flow control
- low-maintenance and leakage-free bearings for axles and rods

All these developments are also ideal for use in museum locomotives to improve reliability and to reduce running costs and pollution.

1 Introduction

The construction of the new SLM rack tank steam locomotives was accompanied by the simultaneous development of numerous components. Most of these can be used to improve the steam locomotives of museum and tourist railways. Of special interest in this context are:

– light-oil firing systems
– electric preheating devices
– insulation technology
– electronic indicating and testing equipment
– sealed bearings
– all-welded boilers

All-welded boilers are more or less common technology and will therefore not be dealt with in this paper.

2 Light-oil firing

The basic advantages of light-oil firing systems are:

– One-man operation is possible. This is most important to achieve economies comparable to diesel or electric traction.

– No fire cleaning is necessary. There are no ashes and no cinders. Modern oil-firing makes the preparation of a locomotive easy, and after terminating the service you can put the engine immediately in the shed without any further attention.

– Cleanest combustion without smoke – not less smoke: **no** smoke. This is most important nowadays if we want to continue and increase steam services.

– Higher efficiency due to superior combustion. Unburnt fuel losses, a big issue with coal firing, are virtually non-existant in modern oil firing systems.

– No sparks and hence no lineside fires. This has become important now even in Britain. Due to the greenhouse effect, the weather is not as it used to be. Ten years ago, you could not go to Britain without an umbrella because it was raining in the morning, followed by rain in the afternoon and completed by rain during the night. So any sparks would immediately be drowned, and there was no danger of lineside fires. But nowadays England can have more sun than the Caribbean Islands, and you may find dry weather conditions for two or three months. As a result of several lineside fires, steam operation has been banned during the summer months. The inherent danger of lineside fires also provides a good excuse for those who don't like to see steam trains operating on their railways. Oil firing is the right answer in both cases (Let me open a bracket here: There **is** a solution for coal firing. Dr. Giesl of Austria invented a micro-spark arrestor in combination with his ejector. In field tests he found that sparks which pass a mesh width of 1.7 mm do not have the ignition power to start a fire. He introduced his system on the old rack locomotives (999.0 and 999.1) of the Schafberg und Schneeberg lines in Austria. Both lines run through forest. The micro-spark arrestor solves the problem of spark throwing, provided the mesh is carefully maintained. In 1992, there was nevertheless a huge forest fire on the Schneeberg line. With the money spent for fire fighting, they could have bought one of our new rack tanks. A rather large hole was found in the mesh of the spark arrestor, but it was decided to blame a cigarette, and since then smoking is prohibited aboard these trains.).

– Modern oil firing is easily adjustable. It can be turned off immediately. The problem on coal fired locomotives is well known: the fireman prepares a big fire whilst approaching a gradient, but operating decides to keep the signal on red for some reason. Where to put the steam? Turning the oil firing system off prevents the safety valves from blowing off.

– Last but not least, a modern oil firing system is much easier to operate. Coal firing requires a skilled fireman, but nowadays it's not easy to get the necessary experience with the limited number of operating days. With today's traffic density on the main lines, one cannot afford to stop for raising steam.

As already mentioned in my previous paper "Modern Steam Locomotives in Revenue Service", the SLM light oil firing system is successfully used on the steam rack locomotives H 2/3. Even at full load, these locomotives work with a perfectly clean exhaust. Now let me briefly explain how the system works. From the oiltank, mounted on the rear of the cab, the oil flows to the burners by gravity. Instead of the grate we have our oil firing system. It contains 5 burners. There is a small pilot burner in the middle and 4 main burners near the corners of the firebox. All burners fire vertically up and the flames do not touch the walls. This is most important to achieve a good combustion with excellent emission values. The oil is atomized by superheated steam. Because of the one-man operation, the engine driver has to drive **and** to fire. To make life easier for him, we developed a one-lever control which automatically adjusts the atomizing steam pressure to the oil flow rate.

It is quite easy to find pictures of old diesel locomotives belching smoke like coal fired steam locomotives. This type of pictures would illustrate what can be "proved" by comparing **old** technology with **new** technology. One of the fundamental faults of the past was to compare **old steam** locomotives with **new diesel** and **new electric** locomotives. As a kind of revenge, we could now do the opposite and compare **new steam** locomotives with **old diesels**. But being serious engineers, we made a serious comparison. We compared the latest diesel locomotive of the Brienz-Rothorn Railway, No. 11, built in

1987, and the new prototype steam locomotive No. 12, built in 1992. In order to make up for the age difference, we upgraded No. 11 in theory with the latest MTU diesel engine. The comparison, based on test results both for steam and diesel, was between 1992 diesel technology and 1992 steam technology. We also calculated the emission values to the power at the cogwheel rim which includes the total thermal efficiency of both locomotives. The results showed very low NO_X-values for modern steam, and Mr. Serchinger calculated that these are very near the theoretical minimum. CO-emissions are also much lower than those of the diesel locomotive; only the SO_2-emissions are a bit higher due to the lower efficiency of the steam cycle.

3 Electric preheater

In Alpine regions the weather is not very predictable. Nevertheless, most people believe in weather forecasts and do not plan a trip when bad weather is announced. If the weather is unexpectedly clearing up, people rush to the station to get up the mountain. Steam railways, also believing in weather forecasts, often had not enough engines in steam to cope with the sudden demand. In order to prevent this, we invented the electric preheating device with which a cold boiler can be put in steam overnight or be kept at any desired temperature, in both cases without supervision.

The function is simple. The electric preheating device is connected to the boiler by means of two flexible hoses. A hot-water pump enforces permanent circulation from the boiler to the electric preheater and back to the boiler. The comparetively low energy input per time and the continuous flow ensure a slow and very gentle heating up. Unlike the conventional method of raising steam with heat transfer from the gas side, all parts of the boiler are warmed up simultaneously. Maximum steam pressure is 10 bar. Control is by means of two thermostats, allowing to keep any set temperature. There are no emissions, of course, allowing to raise steam even in a shed without a chimney. With steam up to 10 bar in the boiler, the engine can easily be moved outside the shed to light the fire, be it an oil- or coal-fired locomotive. Connecting and disconnecting the two flexible hoses each takes about 5 minutes, compared to a couple of hours with the traditional method. Thus the electric preheater saves a lot of man-hours.

4 Insulation

Insulation is most important. At full power, radiation losses are quite small, say 2 to 5 %. This was leading, or rather misleading, many engineers to believe that it is not worthwhile to tackle these losses. But it is clear that the losses become relatively bigger at low powers, and when the engine is standing there are more or less only radiation losses. Now most locomotives usually work only 5 to 10 % of the time at full power, but radiation losses occur 100 % of the time when the engine is in steam. Even a small 0-4-0 locomotive has radiation losses in the order of 20 kW if the boiler is not insulated. On large mainline engines, radiation losses amount to between 100 and 150 kW. By multiplying the radiation losses times the hours the engine is in steam, one can easily realize how much energy = fuel = money is wasted. Insulation material is not expensive anymore. Therefore it is a good option to improve the service of the locomotive and to save energy.

Of course, the full benefit can only be gained with a firing system that can be turned off completely like the oil firing. On a coal fired engine, some of the energy saved by the better insulation will be blown off the safety valves. However, there is still a tremendous gain when the boiler presssure is not on the red mark.

5 Modern measuring technology

Measuring technology made big progress during recent years, and it pays to take full advantage of it. Let's look at indicating as an example. With an indicator diagram, one can determine how much work the engine is doing and, in combination with the speed, how much indicated power is being produced. The indicating diagrams also allow to check the accuracy of the motion as well as the valve timings.

Traditionally indicating used to be done mechanically. I gained experience with that method in South Africa. Under the direction of David Wardale, I was responsible for the mechanical indicating of the famous "Red Devil" (SAR class 26 3450). I had to sit in front on the buffer beam, protected by a provisional shelter only, at speeds up to 100 kph. This was quite an adventure. The feeling was comparable to the one on a rollercoaster. Fortunately, there was no lorry on the track. Sitting next to the smokebox, there was no way to hear anything but the roar of the exhaust, so communication was by hand signals. For each pair of diagrams, new paper had to be wrapped and fixed on the indicating drum, which was time-consuming. So it was difficult to take enough diagrams and at the right time. And there was hardly a chance to record something unpredicted like slipping of the engine.

Already on the "Red Devil" we tried the electronic indicating method. David Wardale's other assistant at that time, Dr. Peter Le Sueur, was responsible for this method. It was soon clear that the electronic indicating was far superior. The whole test trip could be recorded on tape, allowing to draw diagrams of any point of the trip.

Today electronic indicating has been refined by SLM to the point that the results are immediately calculated and printed by the computer for quick analyses.

6 Sealed bearings

Plain bearings commonly used on steam engines have several disadvantages. They are not very reliable. They need a lot of maintenence and – very important nowadays – they loose litres of oil. And who knows how long the environmentalists will close both eyes to overlook this! It is in any case better to have a technical solution ready now. As a matter of fact, two solutions already exist:

- roller bearings
- floating bushes

Both principles have some advantages in common. Both types can be grease-lubricated and fully sealed. If properly designed, there is no leakage. They need less maintenance. Longer service intervals save man hours – you do not have to walk around the engine with the grease- or oil-gun every day or every trip any more. Roller bearings have less rolling resistance, giving a slight gain on tractive effort. And – most important – they are environmentally friendly.

SLM is currently equipping a 52.80 class locomotive with that technology. The idea is to apply most of the modern technology used on the rack locomotives to a standard gauge locomotive. Unfortunately the budget did not allow for a new locomotive, but it will be extensively rebuilt. New axles, axleboxes, pins, rods, pistons, piston-rods, crossheads and crosshead-guides will give the rebuilt engine a smoother ride with less maintenance.

The floating bushes need less radial space than the roller bearings. We successfully use bearings with floating bushes on the connecting rods of the new rack locomotives.

7 New orders

SLM is going to build steam engines too. Lake Geneva has eight paddle ships, four of which are genuine steamers. The other four were converted to diesel-electric drives about 40 years ago. The steam engines are still going strong, whilst the diesel-electric drives have reached the end of their economic lives. SLM proposed to replace the diesel-electric drives with genuine new steam engines. In order to reach a comparable economy, the new steam engines will be operated from the bridge, thus not requiring additional staff as compared to a motor ship. The first of the "re-steamized" paddlers will re-enter service in 2001.

8 Postscript (November 2000)

All of the modern steam technology developed by Swiss Locomotive and Machine Works (SLM) is now entirely in the hands of a new company named

Dampflokomotiv- und Maschinenfabrik DLM Ltd.

DLM Ltd. is active since July 2000. It was founded by the members of the SLM steam team and the Swiss firm "Hug Engineering". DLM Ltd. exclusively purchased all SLM know-how of modern steam technology as from 1950 and intends to continue production and development of new steam locomotives as well as steam engines for ships.

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7 - 301’2 Light General Purpose Locomotive Type

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Today's there is a large diversity of local railways besides the large mainline network: there are industrial railways as well as an increasing number of tourist oriented railways that in one way or the other belong to the historic or nostalgic scene. While most all of the first category are fully dieselised, the latter often run steam for purpose. However, certain aspects that can be built only into a steam locomotive would be of great advantage for addressing some special problems on industrial railways – such as work in enclosed areas where a zero emission engine is desirable.

I. General

This project features a new steam locomotive for light all purpose duty that offers a much better performance to price ratio than contemporary diesel locomotives. It also offers a number of specific technical advantages by its inherently low working noise level and its ability to work temporarily without combustion gas emissions relying on boiler energy reserve. External combustion by itself can be made much cleaner than that in the diesel process. By these characteristics the engine is much better acceptable to the environment as well as for work in housing areas, is suitable even for indoor work and restricted areas such as warehouses and industrial fire hazard areas, for underground sections of a network and for stations and streets.

The design features a new boiler type, designed for oil-firing, combined with the existing chassis of the fireless type '03' as built by Meiningen shops of DR in the 1980s and is to be equipped with the author's throttle & valve handling and a new valve gear.

It is combined with a tender that -a- provides enough supplies for a whole day work shift and -b- by its articulation to the engine provides the vehicle with a much improved riding stability so that a higher regular service speed limit can be agreed over the standard diesel 0-6-0 type.

Use of the very sturdily built existing chassis, of but low mileage still, allows to keep construction costs much lower in comparison to a diesel engine of equivalent performance. Use of the existing cast cylinder blocks again helps to minimise construction costs since these are expensive components to make, especially if blocks were to be made by casting which is generally superior to welded construction in durability and trueness in service. The same applies to castings of spoked wheels.

II. The 301’2 Type

1. Boiler

The engine is to be equipped with a boiler of new design which is the major component to be manufactured new. Although of basically regular type the design is, first of all, fine tuned by the ratios of water and steam volumes, direct / indirect heating surfaces and superheating surface in such a way that it is capable of -a- compensating, by its large heat storage, the highly intermittent steam demand in services such as typical industrial railway work including a large part of shunting, as well as -b- freely attaining high steaming rates when working to engine capacity in local freight or on weekend passenger excursions on local lines, including frequent stops and restarting as well as hilly sections.

While an amount of heat storage capacity in the boiler is typical of steam locomotives, the capacity of this boiler is so increased in relation to its size that it enables the engine to work emission free with oil-firing *cut off* while shunting into closed areas such as tunnels or industrial ware houses or underground line sections. In contrast to the fireless type formerly used for this kind of work the engine remains independent from the latter's refilling station and can work continuously by restoring full boiler heat level with oil-firing *on* while working outside the critical line sections. This is a clear advantage over the usual diesel locomotive as anyone will confirm who had to work in a shed near a running diesel engine. The exhaust steam the engine emits when – and *only* when! – pulling is fully neutral as regards health and environment, yet for extended indoor work a condenser is optional and that would make the engine equivalent to an accumulator electric, emission-wise, while superior in work capacity.

In order to use further existing parts, especially for auxiliaries, as well as to use standardised procedures for maintenance the original boiler filling pressure of 20 bar of the former fireless engine is retained with the new boiler although 22 – 23 bar pressure would have been possible within weight limits. It is however a principle of the author's never to increase mechanical stresses in any used parts over those found in the original design, but rather to seek to *decrease* stresses in the new engine! In view of using the existing chassis with its general simplicity – well suited for the kind of service the engine is proposed for – and in view of the large cylinder volume it is only sensible, therefore, to respect the existing standards and to economise by lower maintenance costs. The boiler is of the largest suitable size within the given axle load of the former fireless – again a limitation to be respected when using the existing chassis in view also of rail transport certification by EBA (federal railway agency) in Germany. Over a smaller boiler, theoretically sufficient for many easier duties, the larger one holds advantages in boiler efficiency and durability by lower heat load peaks on heating surfaces, namely those of the firebox.

The superheater is to be of the French 5P4 type or the 7Q6 type derived thereof by the author. It is to provide 440 °C around 2/3 nominal steaming rate which is essential for the thermic efficiency of the steam engine.

The draughting arrangement incorporates the author‘s de Laval Q6C tuyère (six nozzle head) exhausting into a round chimney of proportions to Dr. A. Giesl's guidelines. The chimney has a diffuser reaching down to the blast head level, quite in contrast to the DR standard simple chimney and nozzle design. This arrangement combines improved pumping efficiency with low noise and over a wider working range keeps ratio of exhaust steam to combustion air volume proportional. Thus, higher combustion rates can be reached at lower back pressure and without shortage of air at high working rates / surplus of air at easy rates which are so typical of conventional draughting arrangements. Highly efficient draughting that holds Lambda rate within a predetermined window according to combustion demands is vital for best boiler efficiency over a widened range of steaming rates and is indispensable with continued very high steaming rates clearly above the established DR / DB respective nominal figures of 70 / 75 kg/m²h for combustion chamber boilers. In the 301♦2 steaming rates can well reach into the range of 100 – 120 kg/m²h without excessive firebox heat loads as this is supported by the boiler's design.

The regulator is of the well proven Wagner type that is both reliable and easy to handle through its characteristic servo-working and which is still available *[1]. It is combined here with the author's invention of combined valve gear and throttle command incorporating a special leverage geometry supporting easy opening and fine adjustment, especially for lower steam chest pressures needed at starting where normal regulators lack steadiness of lever-to-pressure relation, or predictability and stability of steam chest pressure – not to speak of ergonomic ease of handling. This is important in view of using the existing cylinders of very large volume in relation to adhesion weight: because the fine tune throttle handling allows sensitive control of the engine's large inherent tractive effort!

In order to increase efficiency as well as to minimise disturbance from feed water (boiler water temperature drop; input of solids) the boiler is equipped with the author’s type A second-stage feed water heater compartment. This device allows introduction of feed water with but minimum if any effect to steaming and to helps keep the firebox heating surfaces clean, which in turn helps to keep maintenance costs down and performance level up. This is so because harmful water contents, including oxygen, sludge of water treatment reacting with water hardness, acidifiers that in a regular boiler lead to local electrolyte corrosion, preferably at the firebox, are all largely disposed with in the second stage preheater.

2. Steam Engine & Drive

A speciality of the design is the use of a linked handling by the author's invention of regulator and valve gear: It allows to use the existing very large cylinders of the former fireless, taking advantage of their large volume for increased steam expansion The combined handling of regulator and valve gear is linked in a way which prevents any settings that would produce excessive cylinder forces or, properly speaking: excessive tractive effort, which would cause the engine to slip violently.

This feature by the author’s invention is vital for use of the existing cylinders of very large volume. The combination linkage allows for but limited cylinder thrust when starting limiting tractive effort to what adhesion will support on dry rails or sanding. Without electronic slip control – theoretically possible but really unnecessary – a normal degree of trained handling is of course still asked from the driver. That said, the engine will pull away sure footed under any regular circumstances.

The large cylinder volume is applied to advantage by linking up early, providing a greater degree of steam expansion than normally found in a simple expansion engine of a comparable type. Running such relatively short cut-offs with regulator wide, preferably fully open, engine efficiency is well superior to that of a comparable regular engine especially at low working speeds since it can be linked up earlier and to a shorter cut-off. The shorter cut-off again is provided by the characteristics of the new valve gear. This way, efficiency is increased over most of the service speed range except start-off and since more efficient use of steam increases power output, performance is improved proportionally without any extra stress on boiler.

Together with the high steaming rate possible this makes for a very powerful engine and therefore, working at boiler capacity the cylinder volume is no more over-sized but just well fitted. Ideally, of course steam chest volume and piston valves as well as steam passages could be larger, but this limitation from the existing cylinder blocks can be accepted to save construction costs. The blocks are to be internally improved, however, by refurbishing and polishing steam passages, fitting new sleeves of larger port area and improved shape factor.

Further, there are new streamline piston valves and pistons, new steam chest heads and cylinder heads. New pistons are not only part of optimising thermodynamic efficiency: of light-weight design, they help to improve balancing of reciprocating masses which in the existing engine is on the low side while full cross-counterbalancing and full balancing of rotational masses is provided as usual in German steam locomotives.

According to cautious calculation the expected thermodynamic cylinder efficiency is 73 %, a very good value for this kind of engine. This of course is not without the new design of valve gear, featuring a much enlarged piston valve travel so that a long lap characteristic is being maintained even at comparatively short cut-offs, compensating at least partly the given smallish valve chest diameter.*[2]

The described characteristics can be achieved with a limited amount of parts made new: while existing eccentric and valve rods can be retained, new return-cranks, expansion links and combination levers are to be provided. In order to further improve the valve gear mechanically as well as in characteristics it is preferable, however, to replace it completely so that design is free instead of having to accept the existing forms and dimensions of eccentric and valve rods – a fully new valve gear should be considered worth the money. Since in view of but decent rotational speeds in this engine all rods can be made of plain cross section which costs less than fluted ones.

3. Auxiliaries

Some of the auxiliaries can be refurbished from the fireless engine since they are still serviceable today by railway shops. These include standard DR steam turbo-generators and two units of DR compound air pumps mounted on the smokebox. The author generally prefers to have *two* air pumps mounted symmetrically left and right sides in his designs for redundancy and faster reservoir fill-up with long trains.

Rotating feed pump, armatures and cooks are of industrial stock supply. Oil-firing equipment for economic, clean combustion is derived from modern industrial type modified to answer the specific demands in locomotive use. In such an adaptation of an oil-firing system for locomotive use it is important to mind simplicity, not getting lost in electronic wonderlands. Yet, the large differences in power output demands ask for a wider regulation range of firing rate than in usual industrial applications. Without it, boiler output would have to be controlled by excessive on and off changes of firing.

4. Cab

Among the components influencing the appearance of an engine the cab holds a predominant position. Its function is to accommodate people working with the engine over possibly long work shifts. Therefore, its shape and arrangement of interiors are worthy of some refined consideration.

Any comparatively small engine is very sensitive to an 'overload' of a cab. Adverse examples of thoughtless or tasteless construction abound with 0-6-0 steam locomotive types. Design aim is thus to combine inner convenience with outer decency fitting to the general outline of engine and tender, visually providing the connecting link between the two and really making them form one harmonious unit of a locomotive.

A design feature is the cab floor, lower in the area behind the boiler and having a step to the elevated side sections underneath the seats. Also, the side sheets of the cab show a set-in at their lower edge. This allows for the external step-board to be in line with the running board and vertically with the cab sides while the cab ladder is set-in, and leads directly to the inner cab floor which is extended backwards right up to the tender front facing the cab much like in the Mestre cab of the former EST railway, France. In spite of what looks like a classic cab with an open 'tender bridge' the cab is fully closed between back ends of the side sheets.

By ergonomic layout all controls and handles are well visible and operable from the seats. Outlook is optimised for this position, too. Seats are of ergonomic, modern design offering all comfort to support fatigue-free working and moving. The cab's side windows have two wings that can be opened independently and are finely adjustable for ventilation. A spacious, veranda-like outlook is provided with both wings of the window fully open and countersunk behind the front part of the cab side sheet. The window frame also incorporates a gutter. Handrail runs above side window and contours the crescent of the front edge of the cab's roof for secure and easy hand grip. The front-view contour of the cab compliments that of the rear part of the boiler with cab side sheets turning into the curve of the roof without a break. Centrally in the roof top there is a pop-up ventilation window.

5. Tender

As compared with a tank engine design which would probably come nearest at hand when considering the shape of the fireless engine, a *tender engine* holds a number of advantages:

- *substantial increase of supplies;* this may be vital for certain types of traction, especially on industrial railway systems, that could otherwise not be served in a practical way for lack of refilling stations and helps to avoid interruption of work while having to refill supplies;

- *clearness and simplicity in design structure;* since the boiler remains free of collaterally mounted tanks or a saddle tank or the like, it is not just much better accessible for control and maintenance but chassis and boiler are spared any extra mechanical stresses from having to support the tanks, regarding that this chassis was not originally designed for mounting tanks;
- *larger power output;* no tanks – no extra weight: so a larger boiler is acceptable within the given axle load limit, providing larger steaming capacity and higher efficiency at average work demands as well as lower maintenance costs as a result of relatively lower working rates in relation to its capacity and in comparison with the smaller boiler of a tank engine at the same given engine output.
- *improved riding;* both engine and tender combined form an articulated vehicle that by means of intelligent design of the articulation can be stabilised at speed, passes through curves smoothly and without the nosing effects typical of 0-6-0 diesel engines as of steam tank engines;

On the latter point: the tendency of diesel as well as steam tank engine 0-6-0s to develop a basically undampened swivelling around the mass centre (nosing and nicking) is a major reason for the generally low speed limits of these 0-6-0 types. This is inevitably caused by the rigidly mounted wheel sets of inherently short wheel base with engine mass centre right or nearly right above the middle axle and overhangs at both ends. The larger the overhangs of engine structures both ends of the wheel base, the more severe are the impacts of rail / wheel flange contacts.

While it is possible to soften these by cushioned lateral displacement of the axles, the stabilising effect gained in the 301♦2 type by the engine / tender articulation holding the engine at the back end is much more effective than any lateral cushioning alone since it amends the problem's source rather than addressing its consequence. Of course, the two principles can well be combined and in the 301♦2 type end axles are equipped with dampened lateral displacement while the centre drive axle has enough lateral motion to be self-aligning in curves which saves flange thrust and wear on the leading axle. *[3]

In general a six wheel tender should be regarded the right size for this engine type and since a number of them still existed on DR as water tank cars or rebuilt to carry snow ploughs at the time when the project was put up, the tender type of steam loco classes 55, 56 and 57 was used – or rather its chassis, since the tank itself has to be rebuilt to accommodate besides water compartment, the water treatment section including dosage and mixing pump plus the safety fuel tank with its auxiliaries. The tender is rebuilt in classic lines completing those of the engine.

The arrangements for controlled lateral displacement are principally the same as in the engine, again the end axles are laterally dampened and the middle axle can move laterally as to be self-aligning in curves.

Since the spacing between second and third axle is shorter than from centre to first, a Beugniot lever might be installed between second and third. This compensates the lateral movement of the two axles and would provide reduced flange thrust in sharp curves running backwards since both axles would then guide the vehicle. Tender axles are to be equipped with roller bearings as the engine's axles already are. Suspension is already compensated between the second and third axle in the given chassis.

For even greater demands regarding uninterrupted working range, a four axle bogie tender could of course be provided, again using existing tender trucks and chassis. This would take up a former US practice of 0-6-0s with bogie tenders. While it would appear somewhat excessive to European eyes the possible special equipment with a condensor, mentioned earlier, could make a bogie tender a practical proposition.

The drawing shows the 301♦2 type as designed by the author with regular tender.

6. Appearance

There was no intention to conceal the fact that this is a rugged and practical small steam locomotive – there is no fake 'modernisation' of shapes, no fashionable shrouding of things. Rather, external shape is to harmonise with function and express the technical character, not belie it. Therefore no attempt was made to conceal the fact that this is a classic type of an engine with a high pedigree, yet it is one of economically efficient design for industrious work. The appearance combines some traditional elements of American practice, namely, with new elements by the author's, completing and harmonising the timeless style of this locomotive type. Much care has been taken to compensate the inherent shortishness of the 0-6-0-type and the small wheels, well suited for the working range but less than ideal for engine proportions. The lines interlacing and according with another result in an appearance that makes the engine look bigger than it is. In that way, ironically, its shape is truer to the engine's work capacity than to its actual size!

7. Performance

Simplified, power output is a function of boiler output and efficiency of energy conversion in the cylinders. The boiler design layout in this project is to provide a large energy storage reserve compared with the size of the engine and this means a large water content in relation to heating surface and a high boiler water temperature which is one of the reasons for retaining the 20 bar boiler filling, i.e. max., pressure of the former fireless although for just the volume of the cylinders a much abased boiler pressure rather near the late R. Garbe's long favoured 12 atmospheres would have done.

On the other hand layout of heating surface and firebox is to realise very high specific steaming rates so that in spite of the emphasis on heat storage there is an ample supply of steam when high continuous output is demanded of the engine. This explains why there is a firebox looking rather large in relation to boiler length, although design refinements in view of attaining and sustaining specific steaming rates in the range of 100 – 120 kg/m²h of course comprise tuning of tubes dimensions, free gas cross section and draughting, plus a multitude of considerations concerning detail design and materials. Last not least, in order to get *dry* steam into the superheater header at such intensive steaming, according design precautions have to be taken, the most simple of which is evident in the high dome as can be seen in the boiler silhouette, taking advantage of the small size of the engine that leaves plenty of room in the loading gauge. However, there is a water / steam separator by invention of the author's inside beneath the dome, too.

Plenty of steam is fine, but efficient use of 20 bar pressure calls for according superheating temperature in order to use high expansion rates. Superheater design and proportional relation of large and small tubes gas cross sections are tuned for 480 °C at firing rates of 45 – 50000 MJ/h. At the author's standard figure of 4000 MJ/m²h heat load of for specific radiation heating surface for calculation of continuous output with fully welded boiler construction and flexible staybolts type of steel firebox, gross production becomes 9580 kg/h with 20 bar / 480 °C steam.

This probably illustrates why the new design valve gear is essential for the engine as a competent mediator between steam production and utilisation ...

Notes:

[1] At the time of writing, Wagner regulators - as well as many other parts of German standard steam locomotives - were still available.

[2] The extremes in running miniature cut-offs to squeeze out engine efficiency – as far as down to mid-gear in some cases in Britain, on some tests in South-America even '-10 %' i.e. back-gear while running forward - were abortive to the drive's mechanics and did not help efficiency. On the contrary, cylinder efficiency has to decline beyond a certain optimum expansion factor typical of a given cylinder tribology in combination with given values of pressure, temperature and rotational speed. This is so because the abasement of mean pressure and mean temperature and the increase of Δt all become excessive then, which in turn is detrimental to efficiency in a reciprocating flow type of piston engine!

[3] This is only possible in combination with the author's special design of rod bearings!

8. Principal Dimensions

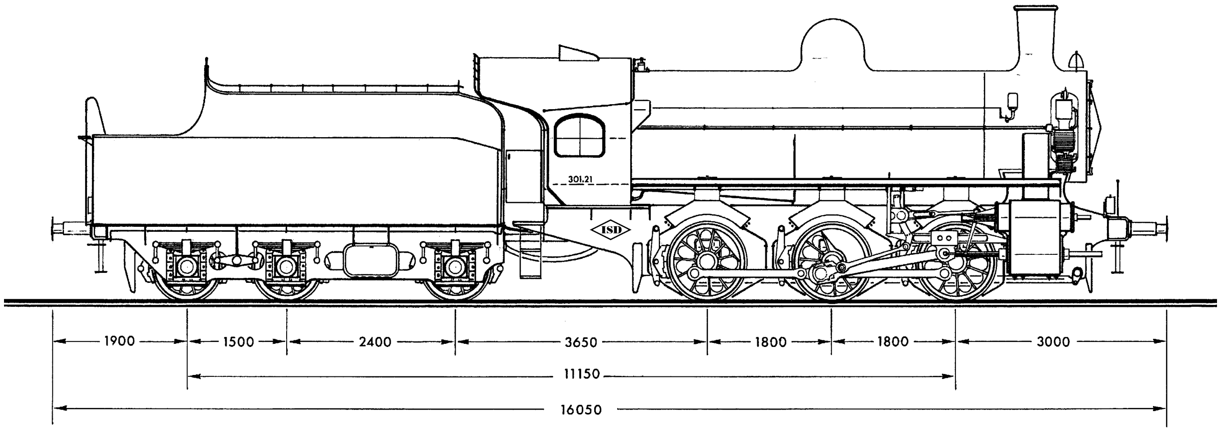
Proposed 301♦2 in comparison with DR standard 89^0 class 0-6-0

Type	**301♦2**	**89^0**	
Wheel diameter	1000	1100	mm
Cylinders diameter x stroke	(2) 660×500	(2) 420×550	mm
Axle load	16	15.6	t
Adhesion weight	48	46.6	t
Boiler pressure	20	14	bar
Firebox heating surface	8.8	6.11	m²
Arch tubes heating surface	3.0	–	m²
Total radiation heating surface	11.8	6.11	m²
Large tubes heating surface	30.9	27.0	m²
Small tubes heating surface	42.6	34.7	m²
Total tubes heating surface	73.5	61.7	m²
Total evaporation surface	85.3	67.9	m²
Heating surface ratio tubes : radiation	6.23	10.1	m²
Superheater surface	40.9	24.1	m²
Length of tubes between plates	3000	2800	mm
Large tubes	(29) 121×4	(28) 118×4	mm
Ratio surface : cross section	342	254	
Small tubes	(138) 38×2.6	(100) 44.5×2.5	mm
Ratio surface : cross section	366	283	
Superheater elements	(6) 20×1.5 *	(4) 30×3	mm
Total gas cross section	3139	3094	cm²
Boiler barrel diameter	1540	1400	mm
Nominal evaporation capacity, gross / net	9.5 / 9.1	4.2 / 4.0	t/h
Nominal power output	1250	426	kW_i
at specific steam consumption	7.28	9.38	kg/kW_ih
at specific heat consumption	22	29.5	MJ/kW_ih
Supplies fuel / Water	4 / 18	2 / 5	m³

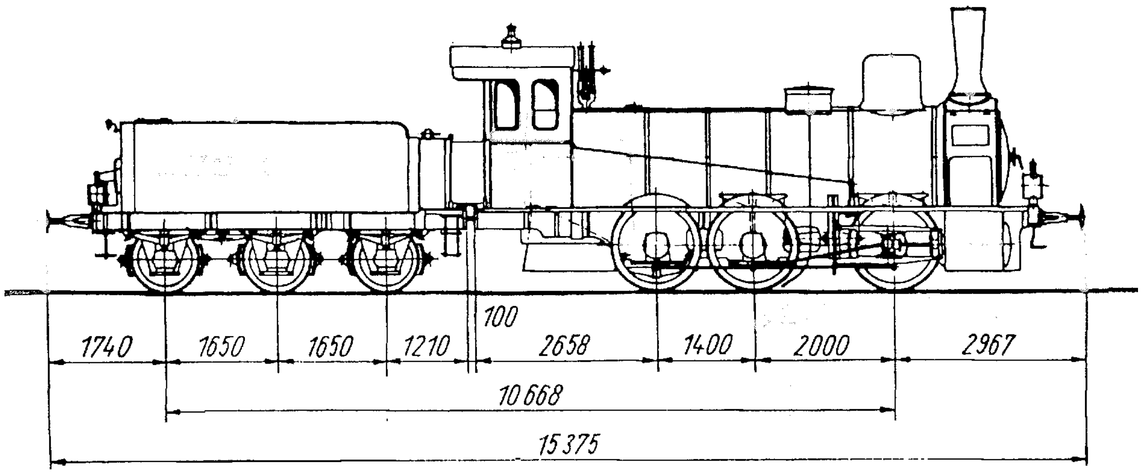
** for in-going superheater elements; plus (1) 50 x 2 return tube*

9. Side Elevation

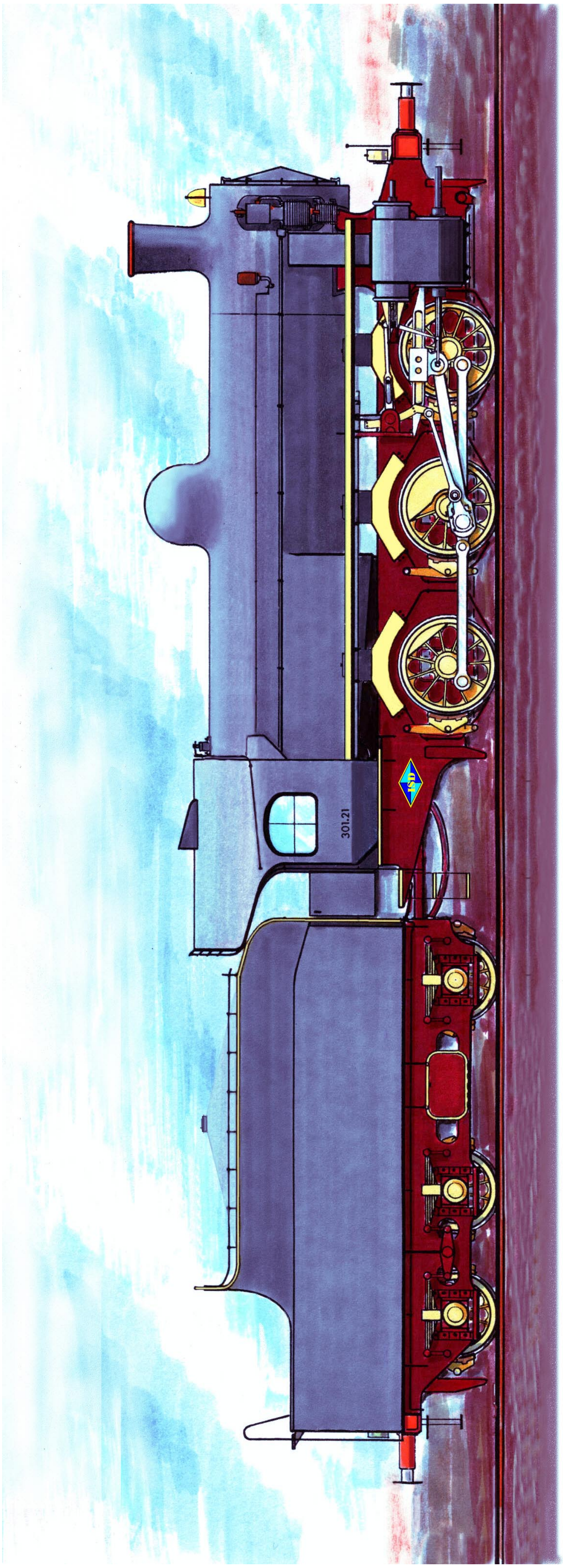
Proposed 301♦2 type in comparison with ex Prussian $G4_1$ type



I.S.D 301♦2 Type – Proposal



Prussian $G4_1$ Type



I.S.D 301'2 Type