‘The fire burns much better ...’

Ph. D. thesis by J. J. G. Koopmans, published 2006

Comments by D. Wardale

The following comments are based on a selective reading of the document that does not claim to be in-depth, but which has nevertheless found errors and inconsistencies. An in-depth reading may be expected to find more, but may also perhaps find answers to some of the following criticisms, which lie buried in the text. Errors and inconsistencies vary from trivial to important; the more important observations are given in **bold type** (minor typographical and arithmetical errors are, for the most part, not considered here). There are a number of cases where what is stated about exhaust design would not apply to a Lempor-type exhaust, but this are not made clear in the work: such cases are pointed out below.

Page 16 item 1.3. The assumption of steady-state flow, which the present work shares with all other exhaust theories, is a necessary simplification. However despite the various quotes in the text claiming effective equivalence between steady-state and pulsating flow, there is a lot of experience to show that the degree of pulsation in a locomotive exhaust does have an effect on steaming ability, and that this effect is positive e.g. see bottom of page 87 and also comments on pages 135-136.

Page 17, Table 1.1. ‘Wardale’ should be dated 1979, not 1982. The former was the date of the Lempor exhaust for SAR 19D No. 2644, which is well documented in the present writer’s book *‘The Red Devil and Other Tales from the Age of Steam’*, referred to in future as *[RD]*.

Page 20, 4th par. The term ‘smoke gases’ is first used here, and subsequently throughout the thesis. It may be objected to because smoke is not a gas but particulate matter (soot). It is this that darkens the exhaust of a locomotive and makes visible smoke. There is no such thing as ‘smoke gas’. The correct term is combustion gas.

Page 20, 4th par. One should refer to ‘induced draught’ when combustion air/gas as sucked through the boiler by creation of a vacuum: ‘forced draught’ refers to air being blown into the boiler at a pressure > atmospheric.

Pages 23 – 103, Chapters 2 – 5. In general, the historical survey is given as it developed, mistakes, ‘blind alleys’ and all. Often the work of one researcher contradicts that of another, simply leading to confusion when all are quoted. Instead of listing all this it would have been more useful to give a *selective* overview showing how and where real insight and progress were made, clearly highlighting the ‘thread’ of genuine progress, as judged by to-day’s knowledge, so that we could trace the path leading to the present state of the art.

Page 54, item 2.12., 5th par. The vacuum – blast pressure relationship is not linear, and this is not mentioned as a ‘conclusion deserving criticism’ on page 55.

Page 55, 3rd par. Chimney : orifice area ratio is confused with chimney : orifice diameter ratio here. The latter is typically ≈ 3 : 1 in modern exhausts (see Table 7.1 and item 7.5.1, page 131) giving an area ratio of 9 : 1, i.e. over twice Clark’s ratio, not less than it.

Page 55, 5th par. Testing has shown that the gas flow resistances through the various sections of the boiler do in fact remain sensibly in the same proportion to each other over the boiler’s evaporative range (*[RD]* page 291).

Page 84. Nordmann’s equation may have been valid for DR standard types, which shared a common boiler and exhaust design philosophy and were operated at conservative ratings with (presumably) consistent quality coal, but it is too over-simplistic for general application, which could have been stated.

Page 93, 1st par. **That the SAR Giesl tests ‘showed that the unit choked itself at higher performance levels’ is diametrically opposite to the truth as written in *[RD]*. Pages 10 – 17 and Fig. 126 of *[RD]*, (the references Koopmans gives from *[RD]* here are wrong) show that the particular Giesl exhaust for the SAR 25NC Class performed better at *high* evaporations and poorly at *low* ones.**

Page 94, 1st par. Fig. 160 of *[RD]* does give a performance curve for the Chinese Giesl exhaust. The question of whether 'the Chinese version had been improved, compared to the original' is probably spurious. Giesl himself improved on the SAR 25NC ejector and presumably the Chinese copied this work.

Page 94, 3rd par. If the comment that Giesl believed "gases could flow at higher velocities than the conservation of momentum would allow" is based on an inadequate treatment of momentum for an exhaust such as the Giesl (see following comments on page 144) then it is not valid. For a Giesl ejector at least some gas momentum should be added as an input, which changes the momentum balance from that taken by Koopmans.

Page 99, last par. In the Porta theory the diffuser acts to convert as much as possible of the mixture flow kinetic energy (k. e.) into the pressure energy mandated by having to pump the combustion gas to atmospheric pressure, and thus reduce the k. e. loss at the chimney exit, i.e. it is thereby a means to more effectively use the k.e. input to the exhaust system. It is not clear that this is the same thing as Koopmans states.

Page 100, 1st par. "The Porta theory ... [has] ... the gas velocity now correctly included". This is most important, and we will refer back to it later.

Page 100, 1st par. '... the basic Lempor concept could be regarded as the ultimate form of a locomotive front end'. Good! Look at other engineering applications of ejector pumps – they look much more like the Lempor than like traditional locomotive exhausts, although the function is in principle the same.

Page 100, 2nd par. Porta stated that the diffuser angle could be greater for the short diffusers typical of locomotive exhausts (at least for large locomotives), although I subsequently found that even for short diffusers it should be a little less than he advocated (*[RD]* page 476). He thought of introducing boundary layer suction to allow a larger diffuser angle. Other authorities (e.g. Kentfield and Barnes, *The Prediction of the Optimum Performance of Ejectors*, I. Mech. E. 1972) have given 80% as an attainable diffuser efficiency.

Page 100, 3rd par. Porta's goal was to increase the power of steam locomotives by as much as possible by increasing their overall thermal efficiency. Power then took care of itself by the equation {power output = input x efficiency}. His exhausts had their part to play in this, and in his Lempor theory he gives a table showing how large were the blast nozzle tip areas of his exhausts relative to the boiler tube bank gas flow area, supposed to be the major factor influencing boiler gas flow resistance, compared to the ratios found for other exhaust systems. In his practical work Porta himself probably mostly used the Kylpor exhaust, not the Lempor, which was a later development of his.

Page 100, item 5.5., 2nd par. Were the locomotives supposed to be smokeless 'due to the large amount of extra air and the high vacuum produced' or because the underfeed stoker resulted in volatile distillation in such a way that it guaranteed that the (smoke-producing) volatiles would be fully burned?

Page 102, Table 5.1. Because of the non-linear vacuum – back pressure relationship, the Clark ratios penalise exhausts which were 'pushed' to higher vacuums (if the Clark ratio is taken at maximum vacuum). The motive in not giving the Clark ratios for the best of Porta's exhausts is not known. The Kylpor exhaust of the Rio Turbio 2-10-2's gave a Clark ratio of ≈ 9.2 at 3 400 Pa vacuum. The best figure (estimated from other test data) for the SAR 19D 4-8-2 with double Lempor exhaust at the same vacuum (3 400 Pa) ≈ 8.6 (*[RD]* Fig. 34). Note that these are based on thermodynamically correct draught and exhaust steam pressure measurements, which does not necessarily apply to all the exhausts of Table 5.1.

Page 110, item 6.3. The data given is over-simplistic. For example, it makes no mention of smokebox resistance, which can be very high in the case of spark arresting and self-cleaning smokeboxes, nor does it acknowledge the high resistance which can occur in the firebox due to turbulent mixing of combustion gas and secondary air (e.g. see *[RD]* Figs. 106 & 107). Overall boiler gas flow resistance for a modern high-resistance boiler is better computed in the manner undertaken for the 5AT.

Page 112, top table. Taking tube bundle cross sectional area as the sole criterion for tube draught loss is inadequate: the equivalent diameter of the boiler tubes must be factored in. In the case of flue tubes this is heavily influenced by superheater element design, which in turn has a major influence on tube gas flow resistance

Page 112, bottom table. Where were the firebox and, especially, the smokebox vacuums measured (both the BR5 and 71000 had self-cleaning smokeboxes, so this question is not academic)? The assumption that the difference between the smokebox and firebox vacuums gives the tube draught loss would be erroneous if these measurements were made some distance from the respective tube plates.

Page 116, 5th par. '... the assumption of a uniform velocity profile for a jet entering a chimney is not supported.' What about the case of Lempor-type exhausts where the exhaust steam jet exits the blast nozzle within the mixing chamber? The curves of Fig. 6.3, page 115, suggest that when the axial distance downstream of the blast nozzle → zero, as it does in such an exhaust where steam and gas first contact each other, the blast velocity → a uniform velocity over the full spread of the jet (i.e. at 45 mm from jet axis = radius of orifice). Koopmans himself assumes this in the 2nd par. on page 116. Therefore it seems that '... the assumption of a uniform velocity profile for a jet entering a chimney' *is* valid for a Lempor-type exhaust. Also the whole argument rests on the Trüpel experimental method of discharging air from an orifice at higher pressure than the air outside the orifice. It is not clear that this will produce identical flow to that from a blast nozzle in which the exhaust steam has been accelerated to high velocity and expanded to smokebox pressure within the nozzle (which it will do whenever the flow is sub-critical - more on this later). It is therefore not clear that the Trüpel results are applicable to the locomotive exhaust, nor Koopmans' deductions from them to a Lempor-type exhaust.

Page 117, Fig. 6.5. Does this apply to a free or confined jet (or both)?

Page 120, item 6.6. Note that as the whole of a Lempor type exhaust is a confined jet (as defined by Fig. A.29.2 on page 454), all contents of this section referring to a free jet are inapplicable to it. That 'about half the available smokebox gas is entrained in the free jet' in a conventional exhaust is no indication that it would not be entrained more efficiently in a mixing chamber. **Equation 6.6.1: using Koopmans' notation on page 107, as the equation is written, as x → zero so Q / Q_o → zero. But Q = total mixture mass flux (i.e. exhaust steam + combustion gas) so in any ejector as x → zero so Q → Q_o and Q / Q_o must → 1. Equation 6.6.1 as given, with no caveats, is therefore wrong. It may only be valid for values of x giving $Q / Q_o \geq 1$, meaning entrainment only starts at x = 3.125d, surely worse than with confined entrainment in a mixing chamber. If equation 6.6.1. is incorrect, all deductions from it may also be wrong.**

Page 124, par. starting 'For practical use ..' If the control volume and its planes are as stated, the assumption of zero gas input momentum in the vertical direction is false for a Lempor type exhaust, where the steam and gas flows are essentially parallel at the nozzle exit plane. Section 7.1. therefore applies only to a free jet type of exhaust (the type for which conservation of momentum is said to apply). The question of the inclusion of input gas k.e. / momentum is considered later.

Page 125, item 7.2. Following from the above, this section also applies to a free jet and not to a Lempor-type exhaust.

Page 131, Table 7.1. If, as appears, Q_m / Q_c is a measure of the accuracy of calculation of exhaust performance using the actual exhaust dimensions and the momentum equation, the correlation is patchy (up to 33% error). Note that the D / d ratio for the 9F Giesl is the lowest of all, and by the 1st par of page 132 should be inadequate (i.e. D /d should be ≥ about 2.8). However the Giesl ejector gave superior performance to the standard 9F exhausts with larger D / d ratios (see Fig. 5.5 page 93). This points to there being other factors at work besides those considered by Koopmans, which may well include the value of accelerating the combustion gas before parallel mixing. As a general point, one may question the whole analysis as BR exhausts had quite mediocre performance.

Page 131, item 7.5.1. The first equation ($Q_1 w_1 = Q_2 w_2$) is not valid for a Lempor type exhaust with a cylindrical mixing chamber as (i) there is not simple conservation of momentum in a confined jet (see page 121 item 6.6.2.) and (ii) the input gas momentum must be added to the l.h.s. of the equation. The conclusions of item 7.5.1. regarding the D / d ratio are therefore also not applicable to a Lempor-type exhaust.

Page 132, 1st par. 2 : 2.8 should be 1 : 2.8.

Page 132, item 7.5.2. x / d = zero for a Lempor-type exhaust.

Page 133, item 7.5.5. Koopmans puts great emphasis on the value of the Euler No. in assessing exhaust performance. However he himself notes it did not meet with universal acceptance in the past, and this doubt continues to the present – for example Mr. Geoff Lambert reviewing Koopmans' work on the Internet states:

"... Jos Koopmans comes to the conclusion that the Euler number is a good criterion for front-end effectiveness because it may measure, in some way, the ability of a front end to create a vacuum. I am not so sure I agree with this ..." As the Euler number is central to Koopmans' work, such reservations are significant.

Pages 135 – 136, item 7.5.7. The important influencing parameter in the pulsating locomotive exhaust may not be so much the frequency of the exhaust beats as the varying intensity of the flow during each beat (this is hinted at in the 3rd par. on page 136, which tends to contradict the previous paragraph). Consider two locomotives of the same class, operating at the same speed and using the same amount of steam. One has even beats, one is 'off-beat'. The time-average exhaust steam pressure of both will be the same, as will the frequency of exhaust beats, but, other things being equal, experience tells that the off-beat engine will steam better. This shows that a factor is at work which Koopmans has not considered, and it is probably the fact that the k.e. and momentum of the flow during each beat continuously vary from release to the end of the stroke and during the exhaust stroke. The mass-average values of all flow parameters will be different from the time-average ones which are measured. Most exhaust steam flow is at release at a much higher exhaust pressure than that shown by the exhaust line on the indicator diagram (which is what counts for cylinder efficiency), and correspondingly higher k.e. and momentum. This increase of mass-average over time-average is presumably intensified by an off-beat engine, which is why it steams better. Thus it is a fallacy to consider pulsations on the basis of frequency alone and ignore the variable intensity of the pulsating flow, and until the latter is incorporated into theory, there has been no real advance in the question of pulsating flow. The analysis of item 7.5.7 is therefore not considered to be significant. Note that de Laval (supersonic) nozzles make the most use of the pulsating phenomenon (see below).

Page 138, 4th and 5th pars. It appears that the function of a converging-diverging nozzle has not been understood. It is a 'diffusing' nozzle only at less than critical pressure ratio, above this ratio it expands the steam to higher (supersonic) velocity than is possible in a plain converging nozzle. As explained above, most steam flows during release, at relatively high pressure, so although the time-average exhaust steam pressure would normally give a pressure ratio across the nozzle < critical, the mass-average flow is normally at > critical pressure ratio and needs a de Laval nozzle to get its full k.e. and momentum potential. Such a nozzle does not therefore cause a 'lower orifice velocity', exactly the opposite during release, i.e. for most of the exhaust steam flow. The 'curious observation' Koopmans notes from the Datong tests is due to the fact that whatever the nozzle area ratio may be it is 'right' only for one particular pressure ratio, yet the pressure ratio of the steam flowing through it is continuously varying, therefore each nozzle tested was only 'right' for a fraction of the total flow, and clearly this fraction did not change significantly for the various nozzles tested, thus giving similar nozzle performances. The question of de Laval blast nozzles is explained more fully in *[RD]* pages 96 – 97.

Page 138, penultimate par. The admission of 'a large "shearing stress" between the large velocity jet and surrounding stagnant gas mass' seems an acknowledgement of the mixing 'shock' loss which is elsewhere dismissed (e.g. see page 116, penultimate par. of item 6.5.2) A stress must be due to a force, and as the jet is moving this must give rise to a power requirement (= force x velocity). This power is certainly used to give momentum and k.e. to the gas, but no thermodynamic process has 100% efficiency, so there must be a (mixing 'shock') loss here.

Page 144, penultimate par. 'A D / d ratio of under 3 ... appears to lower the general level of the calculated theoretical *Eu*.' But the Giesl 9F D / d is only 2.23 : 1 (Table 7.1.) and its measured and calculated *Eu* numbers (said to be a measure of its actual performance and its maximum potential performance respectively) are the best of all the exhausts considered in Table 7.2. A factor in this is that the input gas momentum is ignored in item 7.5.1. explaining the significance of the D / d ratio, but at least some of it must be included for a Giesl ejector (and all in the Lempor). The better performance of the Giesl ejector (or similar exhaust) than might be predicted by the D / d ratio is because there is this added input momentum in the form of accelerated combustion gas. This would seem to negate the D / d ratio is a definite yardstick of performance for all such exhausts.

Page 145, 5th par. This paragraph appears completely at odds with Table 7.2. which shows the highest *Eu* to be for the Giesl BR 9F. Although the SR Merchant Navy shows up worst in the Euler number analysis, this class had an excellent reputation for steaming, both on test and in service and up to what were, by UK standards, high evaporations, which, frankly, could not have been realised with a poor exhaust. This again casts doubts on the validity of the Euler number as a definitive exhaust criterion.

Page 147, last par. The Lempor theory allows both a single and double chimney arrangement to be predicted (in fact any number of chimneys), the steam and gas flows for each chimney of a double exhaust being half the total. Whichever gives the largest blast nozzle tip is the better – it will inevitably be the double.

Page 148, penultimate par. We have the Giesl shape again, the thermodynamic validity of which is open to question. The oblong chimney may well be a cross between a free and confined jet, and therefore difficult to analyse.

Page 149, penultimate par. of item 7.7.4. Even with the blast discharge at the inlet of the mixing chamber, the Datong tests indeed showed the advantage of multiple nozzles, allowing a shorter mixing chamber. This is confirmed by implication in Kentfield and Barnes, *The Prediction of the Optimum Performance of Ejectors*, I. Mech. E. 1972. The number of nozzles is therefore not 'almost irrelevant' in the Lempor, and to link the number of nozzles solely to the orifice – throat distance has to be over-simplistic.

Page 152. The data used for the 26 Class is mutually incompatible: the tabular data is from the exhaust calculations, i.e. for a blast nozzle steam flow rate of 23 150 kg/h, the gas mass flow rate from measurements at the originally calculated smokebox vacuum of 4 423 Pa (but the exhaust dimensions were based on a vacuum of 4865 Pa, see note (5) on Table 26 of *[RD]*). However due to the higher-than-calculated overall boiler draught requirements (see *[RD]* pages 292 – 293) the draught required for a gas flow rate compatible with a blast nozzle steam flow rate of 23150 kg/h is actually higher than 4423 Pa, therefore the gas mass flow rate should be taken at a higher draught (> 5000 Pa). The gas flow taken by Koopmans of 41975 kg/h is therefore significantly lower than it should be. This can quite easily be seen, because a blast nozzle steam flow rate of 23150 kg/h means a total cylinder steam flow of some 28350 kg/h (calculated value) as not all cylinder exhaust steam goes to the blast nozzles because of steam to the feedwater heater and gpcs (see *[RD]* Fig. 127). If 28 350 kg/h of steam at some 450^{o} C (+ saturated auxiliary steam) could be generated with a combustion gas flow of 41975 kg/h we would have done pretty well (ratio of gas to steam flow = 1.48 : 1). Alas not! The calculated gas flow was 55224 kg/h (not given in *[RD]*), which is 32% higher than the figure Koopmans takes. From *[RD]* Fig. 127 the exhaust steam pressure at a blast nozzle steam flow rate of 23150 kg/h is also >> Koopmans' calculated 45575 Pa, in fact it is about 97000 Pa at the exhaust chambers, or from *[RD]* Fig. 123 about (97000 / 1.28) = 75800 Pa total pressure at the blast nozzles, or 66% higher than Koopmans' figure. Koopmans' claimed confirmation of his calculated figures by the 26 Class data is therefore based on incompatible figures and cannot be supported (and one must also remember that the 26 Class data is only as good as the often imperfect measuring allowed, which has been acknowledged on page 253 of *[RD]*). If compatible figures are used, there can only be one of two results. Either there is no longer good agreement, in which case the 26 Class data does not verify the calculation method, or there is, which means that the approach is insensitive to the input data and therefore of dubious worth (generally, if different data can be inputted and the same result comes out, the method is not suitable for processing the input data meaningfully).

Page 153, last par. of item 7.9.2. Diffuser angle is 12^{O} for a short diffuser (see earlier comments on page 100, 2nd par.). Orifices were angled to get more uniform mixture velocity at the diffuser entrance to improve diffuser efficiency (see last par. on page 146) and especially to avoid the problem Koopmans gives in the 1st par. of page 146. Koopmans claims the orifice inclination appears too large and doubts that 'this [inclination] would give a sufficiently developed flow' at the diffuser entrance, but he does not say what to do to improve matters (note that the importance of placing and/or angling multiple nozzles to increase mixture velocity near chimney walls is acknowledged by Koopmans on page 443).

Page 153, 1st par. of item 7.9.3. If the draught of the MN class was 'good' and the combustion 'never very good' then one must look elsewhere for the problem. 'Over-draughting' can produce combustion problems of its own, and one can look, for example, to over-rapid release (itself a sign of a free exhaust) and to firebar design as important factors. This is well covered in chapter 2. 3. of *[RD]*, and the first application of the Giesl ejector to the Chinese QJ Class was reported as giving very poor combustion because the rapid release tore the fire.

Pages 155 – 156, section 7.9.4. (see also comments on pages 461 – 464). Koopmans criticises the 5AT exhaust but there are a number of erroneous assumptions and conclusions here:

1. **The criticism has been based on what has appeared on the 5AT website, but what counts is the (unpublished) detail exhaust calculations.**
2. **The data given for the 5AT in the table is the data originally estimated as the starting point for design, which has been superseded as a result of completing the fundamental design calculations. There is not much change to the data given except that no fixed chimney length (given as 1 840 mm)**

can be given: chimney length depends on its diameters, e.g. the UK moving structure gauge is such that it does not allow the top of a large-diameter chimney to go to the upper limit of the gauge, by an amount that depends on the chimney exit diameter – the larger this is, the more the chimney must be depressed.

3. **'The values supplied must be questioned'. It is most remiss to imagine that the 5AT data can be found by simply extrapolating BR5 data – does Koopmans think the 5AT performance can be realised by simply 'pushing' the BR5 to higher evaporation? Internally it is a totally different boiler, with a different tube layout, different superheater elements having fins which give high gas flow resistance in the flues, a different combustion system and a combustion air pre-heater. Enough has been written in *[RD]* to show how getting higher efficiency from a boiler requires higher draught, both for a more efficient combustion system (high draught due to turbulent mixing) and more efficient convection heat transfer. The data for the 5AT is not assumed – it has been calculated.**
4. **Koopmans assumes the 5AT will have a Lempor exhaust. This however is not the case. Exhausts were worked out by both the Lempor theory and by the data given in Kentfield and Barnes, *The Prediction of the Optimum Performance of Ejectors*, I. Mech. E. 1972. The latter gave a slightly larger blast nozzle area and was therefore preferred, i.e. as it stands at the moment the 5AT design does not have a pure Lempor exhaust.**
5. **Koopmans data at the top of page 156 does not correspond to the dimensions resulting from applying the Lempor theory. The nozzle area is close, but what are the figures for chimney exit and throat areas? Those given are much too small for the overall figures for a double chimney and too large for those of one chimney alone. They will be affected by the length : diameter ratio taken for the mixing chambers, but as Porta recommended 2.5 : 1 in the Lempor theory, later reduced to 2 : 1, this latter figure should be retained as a minimum to be true to Porta's concept. It is presumed the figures given are per chimney.**
6. **The 'requested' Eu number of 0.0537 is calculated from Eu = $\Delta p / \rho_n.V_n^2$ (Appendix A32). However as explained in the comments on pages 461 – 464 this does not represent the required Eu for a Lempor-type exhaust in which the gas has a significant input velocity (and therefore momentum) in the direction of the chimney axis (i.e. assumption 3 on page 461 does not apply – the fact that it is necessary to include it in A.32 shows that the results would be different otherwise). Because of this the 'requested' Eu would be < 0.0537. Alternatively, if Eu = $\Delta p / \rho_n.V_n^2$ is retained, a term must be added to all equations in A.32 giving Eu from exhaust proportions to account for input gas momentum. Equation A32.9 becomes: Eu = $\{R_n(1 - ½rR_n(M + 1)^2(1 + R_c^2)) + (1 - R_n)k^2/r_g\}$ where $r_g = \rho_n / \rho_{gas}$ and k = {gas velocity at base of mixing chamber / V_n}. The gas velocity at the base of the mixing chamber is dependent on chimney design, just as V_n is dependent on blast nozzle design. Taking Koopmans' Lempor figures for comparison purposes only and substituting into the above equation gives theoretical Eu = 0.0841. Using Koopmans' ratio for the practical : theoretical values of Eu, i.e. 0.0359 / 0.0452 = 0.794, gives a practical Eu number which the Lempor exhaust would be expected to deliver of 0.0841 x 0.794 = 0.0668, which is > the requested Eu of 0.0537, i.e. the Lempor exhaust would more than deliver the required Eu. The statements that the Lempor dimensions 'would thus not sustain the requested Eu number' and that '... the locomotive would be 300 – 500 Pa short of its intended vacuum' therefore have no validity.**
7. **The figures for Koopmans' proposed design appear sub-optimal. Firstly, a (mixing chamber + diffuser) length of 1840 mm, to which must be added the vertical height of the bell-mouth gas entry section, will place the latter so low in the smokebox as to restrict gas entry into the chimney. Secondly the mixing chamber length : diameter ratio of only one appears too small to give a uniform velocity profile at entrance to the diffuser, which will adversely affect diffuser efficiency. If we could use such a short mixing chamber we could certainly improve both the Lempor and Kentfield and Barnes figures by having a longer diffuser, but experience (such as the Datong tests which showed the best mixing chamber length : diameter ratio for an exhaust such as now being considered to be about 2 : 1, see *[RD]* page 476) tells that this is not advisable.**
8. **Koopmans' has emphasised the D / d ratio as a yardstick of exhaust capacity, see item 7.5.1. The following figures apply to his proposal and the 2 designs worked out in the 5AT fundamental design calculations. Required ratio of mixture : exhaust steam = 3.22. Ratio D / d, where d = diameter of a single blast nozzle of area = Σ area of multiple nozzles: Koopmans' proposal = 3.25 : 1, Lempor = 2.96 : 1, Kentfield and Barnes = 2.63 : 1. Koopmans proposal therefore matches his D / d criterion expressed in equation 7.5.1.1, but as explained in the comments on page 144 this criterion is not valid for a Lempor-type exhaust.**
9. **To summarise: the 5AT design presently does not use a pure Lempor exhaust; a design to the work of Kentfield and Barnes gives superior blast nozzle tip area despite its chimney proportions appearing to be further away from the optimum according to Koopmans' criteria. The use of the equations in**

Appendix 32 to analyse the 5AT exhaust appears incorrect, as are therefore the conclusions drawn from the analysis. And there are objections to Koopmans' alternative proposal for the reasons given in (7) above.

Pages 158 – 159. Many of the suggested methods (e.g. steps 1, 2, 7, 8 and 9) are from old formulae that should not be used for modern design. In step 3, what is the 'normal range' for a modern locomotive? In step 4, why is there such a piston speed limit – the 5AT will exceed the range given, as have several designs in the past? Generally, the methods given for determining the various parameters can only be supported purely as an example of using the old Eckhardt method. The type of approach used in the 5AT fundamental design calculations should be used for any modern design.

Page 161, 'New design features'. The B1 was a class 5 locomotive, not class 4, under the BR classification scheme.

Pages 167 – 182, chapter 8. Diagrams of the various exhaust arrangements tested would be helpful.

Page 178, 1st sentence. This is not true if, as it should be, the total (Pitot tube) exhaust steam pressure is taken, see *[RD]* footnote on page 128.

Page 178, 2 bulleted items at bottom of page. (1) This statement is only valid for an exhaust system that fully complies with the momentum treatment given in section 7.5.1. Not all exhausts do. (2) Objection is raised to the Q / Q_o equation, see comments on page 120.

Page 179, 1st par. The gas flow resistance through the firebox (furnace) and smokebox, which may reach very significant values ([RD] page 292) is ignored.

Page 180, Tables 8.3. and 8.4. The data of these tables does seem credible – the very large discrepancies between the calculated and measured exhaust steam pressures means that one (or both) of the respective figures must be wrong. Note that the calculated figure is always the higher, which is opposite to the case of the 26 Class exhaust given earlier (see comments on page 152). No mention is made of excess air – it is clear from the data that there must be excessive excess air with the smaller orifices.

Page 181, Conclusions from tests, 3rd par. How is 20% excess air 'estimated'? In practice it can vary widely and can be calculated from measurements.

Page 182, Momentum. States that momentum from single and multiple orifices is approximately the same. But we have ample evidence of the superiority of multiple orifices (page 182, last par., page 184 item 9.1.3, last par.) which (again) suggests that other factors are at work. There does not seem to be anything in the momentum (or energy) approaches to exhaust design that can account for the improved results with multiple orifices, rather more rapid 'mixing' (momentum and energy transfer) is probably the key. How can the better performance of multiple compared to single nozzles be squared with the statement that 'No specific addition to the [Zeuner single orifice] theory for multiple orifices is needed' (page 182, 4th par.)?

Page 183, item 9.1.1, point 5. Porta was well aware of the non-uniform velocity profile in an ejector, which it was aimed to make as uniform as possible in the Lempor mixing chamber before the start of the diffuser, e.g. by using multiple nozzles at an angle to the chimney axis. As is pointed out in point no. (7), a non-uniform flow pattern is essential at the start for gas entrainment, but once entrained the mixture flow must then be made as uniform as possible over the full flow area, hence the need for adequate mixing chamber length.

Page 183, last par. 'The velocity of smoke gas should be disregarded *if the orifice is at a distance from the chimney*' (my italics). But if it is not, as in the Lempor, then it must be included (this is confirmed in the 1st sentence on page 100). This adds significant k.e. and momentum input to the exhaust and is important in view of its non-inclusion in Koopmans theory, see later.

Page 184, 3rd par. If a minimum mixing chamber length : diameter ratio and maximum diffuser angle are accepted, it is the allowable chimney length which will determine its diameters. In other words, in a practical exhaust design, chimneys of different lengths would have different entry and exit areas, at least with the Lempor theory.

Page 184, The tests with the RTM 56 and 54. See comments on page 182 above.

Page 184, ‘The single orifice ...’ ‘There is little wrong with it ...’ This ignores the fact that with larger locomotives it simply isn’t possible to maintain good ratios with a single exhaust because of the height limitation. This is what is wrong with it. And if, in the previous paragraph, it is stated that with four orifices it is ‘possible to use a far larger orifice area than if one uses a single orifice’, how can it now be stated that ‘There is little wrong’ with the single orifice?

Page 184, last par. See comments earlier on page 148.

Page 185, Lemaitre. Should be ‘converging – diverging’ orifices, not v.v.

Page 185, Giesl. The experience from the SAR tests is that a wider throat was just what made the Giesl ejector performance fall off at low loads, see comments on page 93 earlier. Giesl himself certainly thought that the 9F Rugby tests with his ejector were ‘proper’.

Page 186, item 9.2, point no. 4. Whilst what is written is correct in principle, in practice the very low power required for most heritage operations means that coal and water savings due to improved exhausts will be marginal. A back pressure close to zero, which is probably recorded by most heritage locos most of the time, cannot be significantly reduced, no matter what the exhaust system. Significant benefit will only be given for locos which are habitually worked hard, which in most cases seems to be for n.g. operations where the locos are very small and the gradients severe. Engines operating main-line excursion trains may also benefit, and improved exhausts give both types of operation the advantage of extra power, which they can both probably use. However this will work to oppose the supposed benefit, point (3) of item 9.2. But as long as rivet counters dominate the heritage movement and the ‘it must not alter appearance’ attitude prevails, getting the optimum exhaust for any engine (which generally involves increasing the chimney diameter, a visible change) is stymied at the outset.

Page 204, 1st par. (Clark). There is support here for the possibility of non-concentric flow of exhaust steam raised in *[RD]* page 475, footnote 2.

Page 204, 2nd par. (Clark). This supports the use of the thinnest practical blast nozzle material.

Page 208, ‘influence of the Capacity of the Smokebox’ (Clark). The original conclusion may well be correct, see also page 210 point no. 15.

Page 229, item A.3.2.7 (Nozo & Geoffroy). There is an optimum blast nozzle area and chimney area for any given locomotive and required evaporative capacity, and it is the function of exhaust theories to give a means of calculating these.

Page 230, adjacent to Fig. A.3.3 (Nozo & Geoffroy). This points to the relative insensitivity of draughting to chimney area near the optimum, i.e. the chimney area can be non-optimal without significantly affecting performance, a point recognised by Porta. This could be said to oppose Koopmans’ item 7.5.1. pages 131 – 2.

Page 231, 4th par. (Nozo & Geoffroy). Shows that (i) a correctly designed ejector remains optimal over a wide working range and (ii) that a front-end limit, i.e. where an ejector can no longer aspirate enough air to sustain the necessary combustion rate, will occur.

Page 233, section A.3.2.8, point 3 (Nozo & Geoffroy). Implies the best chimney is one which starts about level with the top row of tubes, however for the longer chimneys in a properly-designed ejector pump for larger locomotives gauge height limitations dictate that their entrance is to be as low as possible in the smokebox commensurate with adequate gas flow entry area into the chimney.

Page 256, item A.9.2.1., 1st par. (Von Borries). Although this is in <> marks (i.e. paraphrased) it can scarcely be believed that it is what was originally written. It would have us believe that combustion gas rising from the front of the fire crosses over that from the back inside the firebox to exit via the upper tubes, whilst that from the back exits from the lower tubes. (!!!)

Page 264, 3rd par. from bottom and pages 265/6, Figs. A.10.1/2/3 (Master Mechanics Association). This appears to show a trend towards some form of the Kordina, and to acknowledge the principle involved, which is, incidentally (and incorrectly), contradicted by point 6 of item A.12.4 on page 275 (Quereau).

Page 268, last par. (Sweney). Mogul should be 2-6-0, not 4-4-2.

Page 289. Equation for ‘b’: b is not given in the notation, page 288: what is it? This is a common fault repeated throughout the thesis, i.e. symbols are introduced in the text without appearing first in the notation or, as here, being defined at all. For example, what are ‘a’, ‘m’, and ‘R’ on page 316 (they are not given in the notation, page 301)? The ‘burying’ of symbols in the text (even if this is done at all) makes it difficult to follow equations. Other instances of this are not commented on further.

Page 304, 4th par. (Strahl). Any fireman will tell you this is far from true! There are a large number of reasons why. Point no. (2) on page 350 is closer to the truth, but does not tell the whole story.

Page 328, 6th par. (Strahl). It ‘should’ make no difference, but it does, see comments on pages 135 – 136 earlier.

Page 334, penultimate par. ‘The introduction of the velocity of the gas at the chimney entrance ... should be regarded as incorrect.’ Koopmans’ argument for its non-inclusion here is that it is *not an independent variable*. But he has already stated that it is *correctly* present in the Lempor theory, see 1st sentence on page 100, which the present writer agrees with. *As according to his argument on page 334 it would appear to be as much a dependent variable in Porta’s work as in Strahl’s, these two different stances are inconsistent – they can’t both be right.* The present writer’s view is that Koopmans’ argument on page 334 is incorrect in principle (this does not mean to imply that Strahl’s precise treatment of gas velocity is correct). The pressure energy in the exhaust steam is partly converted by acceleration in the blast nozzle into useful kinetic energy: its total energy (neglecting friction losses) remains constant by the Bernoulli equation. A vacuum is thereby created in the smokebox and the (pressure + kinetic) energy of the combustion gases in the smokebox is determined by this vacuum, the k. e. of the relatively slow-moving gas being small. At any point where the gas velocity → zero, say next to the smokebox shell wall, we have the true (stagnation) vacuum. It is from this stagnation vacuum that the gas pumping work occurs (and not, for example, from the much higher vacuum existing at the chimney choke, see quote from Ell on page 95), and it is the corresponding stagnation or total pressure energy of the gas that is *dependent* on the vacuum created by the exhaust. But just as part of the pressure energy of the exhausting steam is turned into kinetic energy, so part of this gas pressure energy can be converted into kinetic energy, to aid ejector performance. The fraction of the (constant) total gas pressure energy (the dependent variable) that is converted into kinetic energy depends on the design of the chimney, as does that of the steam on the blast nozzle design. Gas kinetic energy is created from the stagnation gas pressure energy in just the same way as the steam kinetic energy is created, by acceleration, and it is therefore valid in principle to include it as an input energy in the energy balance for suitably designed ejectors, such as the Lempor. This is what the Lempor theory does, but Koopmans’ work does not.

Page 338, 2nd par. (Railway Engineer). The piston theory is wrong, but there must be some difference between pulsating and steady flow, see comments on pages 135 – 136. To measure this, any experiment must attempt to reproduce the highly non-uniform exhaust flow from a locomotive, i.e. a release flow that is much larger than the overall time-average flow. The Datong tests attempted to do this, see *[RD]* page 475.

Page 338, 4th par. (Railway Engineer). Note the recommendation for de Laval blast nozzles.

Page 343, item A.18.2.3, 2nd par. (Railway Engineer). Note recommendation for bell mouth shape.

Page 347, last par. (Legein). The term ‘temperament’, whilst linguistically correct, would probably be better rendered in engineering English by something like ‘characteristic’.

Page 351, 4th par. from bottom (Legein). Note the hypothetical conclusion that mixing loss → zero as no of petticoats → ∞. This is supported by page 371, 3rd par.

Page 354, last par. (Legein). 16 mm should be 16 mm / m, or more simply in current notation 16‰. Same for ‘3 to 5 mm’.

Page 360, top par. (small letters). The term ‘shock’ has a specific thermodynamic meaning and refers to sudden pressure rises in supersonic flow. Therefore its use here is open to question, especially for simple convergent blast nozzles for which the blast is not supersonic, although part of the steam flow from a de Laval blast nozzle will be supersonic and a genuine shock may occur. To distinguish exhaust losses from true shock losses the present writer prefers ‘mixing shock losses’ or simply ‘mixing losses’.

Page 365, 1st par, paraphrase from Giesl. There are mixing, friction, and exit k.e. losses in the exhaust system, and the Lempor aims to give the highest overall efficiency by minimising the sum of these. Giesl’s approach appears to be to reduce mixing losses by a mixing zone of very restricted area at the expense of a smaller-than-possible chimney exit area (as for a given chimney length the latter is fixed by the former and the allowable diffuser angle) and therefore relatively high exit k.e. loss.

Page 374. item A.21.14, point 2 (Chapelon). This doesn’t make sense as written: presumably it should read ‘Thanks to the decrease in back pressure the boiler needs to produce less steam, ...’

Page 374, item A.21.16 (Chapelon). ‘Fire-bridge’ should presumably read ‘brick arch’. Note that Chapelon’s thinking as given here is at variance with the thinking behind Porta’s g.p.c.s., which the present writer prefers.

Page 378, Fig. A.21.8 (Chapelon): the Kyläla spreader is clearly seen to be the inspiration for Porta’s Lempor blast nozzles.

Pages 396-7, item A.24 (Godfernaux). This appears to be a simple and illuminating explanation of the steaming phenomenon.

Page 403, item A.25.3.2, page 405 last par. (Young) and page 429 top par. (De Gruyter). The previous remarks in connection with pages 135-136 apply. As the experimenters are adamant that draught production is essentially the same with pulsating as with steady flow, and as the practical experience on actual locomotives points to it being otherwise, one may have to look at the *effects* of pulsating draught on heat transfer and combustion, rather than at the effect of a pulsating exhaust on draught.

Page 408, item A.25.5.3 (Young). This supports the use of a Lempor-type exhaust, and of multiple chimneys where available height is inadequate.

Page 408, item A.25.5.4, 2nd par. (Young). Note advantage of smaller flare where nozzle is close to chimney, e.g. see Fig. 7.17.

Page 408, item A.25.5.5 (Young). The conclusion is effectively for a Lempor-type exhaust of cylindrical mixing chamber and conical diffuser (although with the blast nozzle (conventionally) below the chimney).

Page 411, point (4) (Young). Shows importance of nozzle form – but where is the theory telling a designer how best to design a nozzle?

Page 431, top par., (De Gruyter). How can the [mixture] pressure at the chimney exit be above that of the surrounding atmosphere when the mixture comes from the vacuum existing in the smokebox (presuming, as it should be, that the exhaust steam is expanded to local pressure in the blast nozzle, and that we are referring to actual mixture pressure, not to stagnation pressure which will always be > atmospheric)? This is effectively saying that the exhaust pumps combustion gas to higher than atmospheric pressure.

Page 434, item A.26.2.6, point 2, (De Gruyter). On what basis are the lines of Fig. A.26.8 extrapolated beyond the test results? That a chimney may have an optimum length, beyond which efficiency decreases, would appear to be true only for very long chimneys (outside the range possible in locomotives) where frictional effects may outweigh other advantages from long length.

Page 440-1, Figs. A.27.1 and A.27.2. (Lemaitre) and page 443, 2nd par. The best results are with long chimneys, supporting the use of enclosed (as opposed to free) mixing, i.e. with a mixing chamber.

Page 443, 2nd , 6th and 7th pars. Supports aiming jets at periphery of mixture to even out its velocity profile, and suggests exhaust performance is quite sensitive to jet position and aim.

Page 444 – 452, Lempor theory (Porta). The presentation of the Lempor theory is mostly accurate, but note the following.

Page 444, 1st par. 'It appears only to be available as an internet document'. The present writer, and others, use copies of Porta's original hand-written document. Strangely Koopmans has not included in his thesis the much more comprehensive 1957 paper by Porta and C. S. Taladriz to the 9th Pan American Railway Congress entitled *'The Exhaust of Locomotives'*, which deals with both the Kylpor and Lempor exhausts. The 1974 Lempor work is merely 'a revision' (Porta's own description) of this earlier work, which is in the public domain.

Page 444, last par, and page 448, 1st par. Porta subsequently changed his recommendation from a converging mixing chamber to a cylindrical one.

Page 447, equation A28.7. F_0 and F_0^2 should be F_b and F_b^2.

Page 448, Koopmans' note in small type under equation (A28.9). The only difference between equations A28.8 (Porta) and A28.8a (Koopmans) is in the final term. $(1 - \xi_b) = 0.96$ (Porta) and $1 / (1 + \xi_b) = 0.962$ (Koopmans), an 'error' well within the accuracy of the calculations as a whole and therefore justifying Porta's simplification on page 447 that $(1 + \xi_b) \approx 1$ for the purpose of these calculations.

Page 448, Koopmans' note in small type 'From quite different orifices'. Yes, but in each case the orifices are of circular section, or nearly so, and internally smooth, i.e. without any tips or projections, which will give similar flow or discharge coefficients. The flow coefficient in the previous sentence = 0.99. The following sentence should read '... for a carefully-designed bell-mouth ...'

Page 449, Koopmans' note in small type. Kentfield and Barnes, *The Prediction of the Optimum Performance of Ejectors*, I. Mech. E. 1972, confirms diffuser efficiency can be as high as 0.8 (for smooth, accurate diffusers). In addition it may be expected to be high in a locomotive exhaust because of the limited length.

Page 449, 5th line from bottom. W1/W should read W_1/W and W/W_b should read W_1/W_b.

Page 450, 1st line. $(F_0 + F) / F$ should read $(F_b + F) / F$.

Page 452, penultimate par. Porta's work is equated to that of Zeuner with the inclusion of the gas momentum, which has been judged as correct (1st sentence on page 100). From his momentum-based approach and tests, Koopmans' has concluded that 'The momentum equation as presented by Zeuner in 1863 suffices for exhaust calculations' (page 183, penultimate par.) It follows that the Lempor theory must also suffice. Indeed we seem to have the equivalence of the energy and momentum based approaches: if the fundamentals of both are correct, i.e. according to the laws of nature, then they are bound to be equivalent, merely being different ways of stating the same thing. As the Lempor theory includes mixing 'shock' losses and yet is equivalent to the momentum approach of Zeuner (where these losses may not need to be considered) it seems to follow that these losses do indeed need to be figured into the energy approach, which Koopmans appears to question (e.g. page 116 3rd par. from bottom and page 388, sentence following equation A22.11).

Pages 453 – 455. Note the difference between a free jet and confined jet (i.e. momentum conserved v's momentum + pressure conserved (the latter due presumably to the effect of friction on velocity building up a pressure gradient in the direction of flow)). The Lempor exhaust is of the confined jet type, but Koopmans seems to consider only conservation of momentum, e.g. on page 459, last par. and in Appendix A32.

Pages 456 – 458. There are significantly more independent variables affecting exhaust performance than listed here, for example number of orifices, geometry of orifice(s), pitch circle diameter at which multiple nozzles are placed, angle of such orifices, gas velocity at mixing chamber entrance for Lempor type chimney (see comments on page 334), freedom of release flow (affected by valve and valve liner design), length of mixing chamber + length of diffuser separately (instead of simply 'length of chimney'), taper of chimney, geometry of chimney bell-mouth, combustion gas properties. The true number of dimensionless groups resulting from the Buckingham Pi theorem is therefore significantly greater than given by Koopmans, and his analysis, item A.30 must be regarded as incomplete / approximate.

Page 461 – 464. All examples given in Appendix A.32 are partly free and partly confined jets (by the definitions of A.29). However the Lempor is all-confined for which (i) according to A.29. there is

conservation of momentum + pressure rather than conservation of momentum, and (ii) the assumption throughout in A.32 that 'Q_g has zero vertical component of velocity' is not valid, and as we have seen earlier (comments on page 334) its vertical momentum must be included, as a –ve term on the r.h.s. of equation A32.2. ***This is important as it will act to decrease the Euler No. required for a given vacuum (or, alternatively, increase the Euler No. produced by a given chimney, see comments on pages 155 – 156 point 6), which in turn answers the criticism of the 5AT Lempor exhaust on page 156, 2nd par.*** **Appendix A.32 is therefore not applicable to Lempor-type exhausts as it stands. Yet it has apparently been used by Koopmans in his suggested Lempor-type design for the 5AT with blast orifices in the mixing chambers (i.e. 'distance *x*, orifice – chimney = 0' on page 156). Koopmans states on this page '... the Lempor design is flawed' and 'The Lempor calculation appears to give a dubious result. A double chimney system should be investigated ... as described in Appendix A.32.' Given the non-validity of Appendix A.32 for such an exhaust, it is suggested that it is Koopmans own proposal that might prove flawed or dubious. Indeed his comments on the 5AT Lempor seem to be based on disregard of his own statement on page 100 that the gas input velocity must be included [i.e. in either the energy or momentum balance]. Note also that Appendix A.32 assumes negligible friction, whereas the Lempor theory makes some attempt to quantify friction (page 447), and after all that Koopmans has written about non-uniform velocities (e.g. see sections 6.5.2 & 6.5.3) uniform velocities have, as in the past, been assumed again, which, whilst it may be a good approximation for v_n, is not so good for v_e and v_{es}. If the earlier insistence on non-uniform velocity is considered one of the work's advances over former theories, where is the advance in practice if this point is now ignored?**

Pages 461 – 464. The Saunders Idealised Theory deduces that the best result (highest Eu, i.e. highest vacuum for a given input momentum flux) is with a cylindrical chimney followed by a diffuser, = Lempor type exhaust.

Page 464, point 1. The admission for the 'ideal *p* model' that when $R_c = 0$ (i.e. when chimney exit area is a maximum) Eu is not a maximum is an indication that the pressure distribution model is wrong, because if $R_c = 0$ diffusing is a maximum and for a given input momentum flux the vacuum created should then be a maximum.

Page 468 – 469. The data used for this appendix is mutually incompatible, see comments on page 152. Any 'fit' of practical and theoretical results is therefore suspect. The chimney throat diameter (item 3 of top table, page 468) is 422 mm, not 211 mm.

Pages 471 – 478, Appendix B.1. In general the methods described are considered a poor substitute for Porta-inspired 5AT-type calculations.

Page 472, item B.1.5. The vacuum measuring tube should end flush with the inside of the smokebox wrapper plate to ensure it measures the stagnation (total) vacuum. Experience is that it never clogs if fitted on or higher than the smokebox vertical centre.

Page 474, item B.1.10. In view of past correspondence between Koopmans and himself in which Koopmans championed the use of the largest possible number of blast orifices, the present writer is amused to see a figure of 'less than about 8' orifices being recommended, the same number as used for a double Lempor. It is the number shown in Fig. B.1.4, page 478, which is effectively a double exhaust changed into one elongated chimney.

Page 475. Table B.1.1, last column. Why 'vacuum decreased by' and negative numbers: should it not be simply 'vacuum increased by'?

Page 477, 4th par. Goodfellow projections, or indeed any type of (invariably blunt) tip or projection into the blast nozzle, are to be avoided because of the high increase in exhaust steam pressure they cause, this in turn because of the reduced flow coefficient of a nozzle with such projections (net flow area is then significantly < nominal nozzle cross-sectional area). Such tips were used in practice on the SAR on exhausts of large diameter but limited height because to get 'sealing' at the chimney choke with limited nozzle – choke axial distance and a presumed steam blast angle of spread the blast nozzle diameter had to be quite large, therefore with such a nozzle, tips (or indeed sometimes a full cross) were used to reduce the nozzle area to that required to give the necessary blast velocity.

Page 478. The proposed BR5 exhaust (Fig. B.1.4.) will, no doubt, improve on the standard BR5 arrangement. But it does not escape the problem of altered external appearance, a major problem with the heritage rivetcounter brigade. Neither does it conform in some of its details to a Lempor-type exhaust, which it has been admitted is the best known (e.g. see page 100 1st par.). Principally, the placing of the nozzles below the chimney means that full input gas k.e. / momentum cannot be used, according to Koopmans himself. The tests at Datong showed this placing to be inferior to having the nozzle tip level with the start of the mixing chamber (*[RD]* page 476). The mixing chamber is too short, but this may be mitigated by the 'free' steam – gas contact occurring upstream of the chimney (which has the above-mentioned disadvantage). Koopmans' proposal is the combination of 'free' and 'confined' jets that is used in 'normal' locomotive exhausts. One may argue that if the effect of a 'free' jet is superior then why have a chimney at all, and if that of a 'confined' jet is superior, then why place the chimney entrance above the blast nozzles? The reason for the historical clinging to this free + confined jet combination which is perpetuated here may be a throwback to the original thought that the chimney entrance should be relatively high up in the smokebox (e.g. see A.3.2.8 page 233 point 3, dating from 1860), also a desire not to throttle gas flow by lowering chimney entrance. The contra argument is, of course, the need to obtain the longest possible mixing chamber, and practical experience on the SAR and Rio Turbio Railway suggests the chimney entrance can be set quite low in the smokebox without net detrimental effect. The given diffuser angle of Koopmans' proposal, 10.5^0, is calculated from the (narrow) width of the chimney only: as in the (longer) longitudinal direction the diffuser is shown as diverging at a greater angle than in the transverse direction, the net diffuser angle will be $> 10.5^0$, Koopmans' recommended value. (If diffuser angle were to be increased to keep a constant exit / entrance area ratio as entrance area increased, it would become ever larger for larger diameter chimneys, which does not seem correct. Fixing the maximum permissible value of diffuser angle therefore favours small exhausts and splitting a single exhaust into multiple chimneys, an important advantage of the latter. It is debatable whether Koopmans' proposal is closer to a multiple exhaust than to a single one.)

Summary. The thesis can be assessed under three headings.

1. **Historical**. The historical survey is probably the most comprehensive ever undertaken, and for students of engineering history should be valuable. But as noted in the comments on pages 23 – 105, the inclusion of so much material, sometimes irrelevant, contradictory, or simply wrong when seen from today's perspective, is not much help to the practical engineer. It would have been better to have been more selective, concentrating on how today's knowledge was gradually built up. That the survey has not included all important material is inevitable – some will simply not have been easily traceable, e. g. that coming from the communist bloc. Mention has been made of the absence of Porta's most comprehensive 1957 paper (see comments on page 444). A work probably untraceable by Koopmans is the lengthy B. Sc. dissertation by the SAR engineer Smith and the resulting 'K-ejector' for the SAR 25NC class, briefly mentioned on page 18 of *[RD]*. Of interest is that Smith independently stressed the value of turbulent mixing *'where the two streams are flowing parallel to each other and at the same order of velocity'*, which sounds rather like the Lempor.

2. **Simple improvements to existing exhausts**. This would mostly consist of the substitution of multiple blast nozzles for a single nozzle, which is cheap to do and does not alter a locomotive's external appearance. As such, it should be attractive to operators of heritage locomotives. Here the thesis is of the greatest benefit. At the request of SAR staff, the present writer did such alterations to various SAR locomotive classes, more or less on an 'eyeball' basis. The results were mixed, as described in Chapter 4 of *[RD]*. At the time the importance of the nozzle – chimney choke axial distance was not appreciated, and had the information contained in Koopmans' thesis been available the results would certainly have been better. However such limited alterations to a locomotive naturally give limited benefit: as written about the SAR work on page 343 of *[RD]* '... this small alteration had given only a small gain and ... it was no substitute for a properly designed exhaust system.'

3. **Advanced exhaust systems for advanced locomotives**. No clear advance over existing knowledge nor new insight nor useful concrete advice on most of the parameters of interest to the exhaust designer can be found in this work. These parameters include, for example, the following factors listed on page 474 of *[RD]*: blast nozzle design (i.e. geometry), de Laval blast nozzle area ratio, distance from the Kordina wall to blast nozzles, use of swirl, mixing chamber length : diameter ratio. Although the importance of some of these parameters has occasionally been acknowledged in the text (e.g. on page 185 under 'The Lemaitre system' on converging – diverging blast nozzles) there has been little or no attempt to investigate them, and we are no further ahead in our knowledge. No mention has been made of the Kordina and blower, both parts of the front-end intimately connected with the exhaust system. Even if Koopmans' work were taken as valid, taken as a whole his presentation is very disjointed. What the locomotive designer needs in such a work is a coherently laid-down methodology for optimum design. This is what Porta did in his various papers, and his Lempor theory is very easy to use – the difficulty lies in accurately estimating the data that must be put into the theory, a problem which applies to all exhaust work. Most importantly, the foregoing

comments have highlighted many inconsistencies in the thesis, and suggested its inapplicability, as it is presented here, to advanced exhaust systems such as the Lempor. Except that it may in some instances point the way to where future research is needed, the conclusion therefore has to be that it is of very limited benefit for advancing the art of locomotive exhaust design beyond what has already been achieved by the work of others, particularly Porta.

Recommendation. Proof of the pudding is in the eating. At the time of the 5AT exhaust design, Koopmans was invited (via one of his associates connected with the 5AT team) to prepare an exhaust for the 5AT for comparison with that being worked out in the fundamental design calculations. At the time he was unable to do this. However the offer should still stand. What is proposed may be as given on page 156 of the thesis, or this may be revised in the light of the foregoing comments. If it is thought to be a realistic proposal, and is sufficiently different from the Lempor or Kentfield & Barnes inspired exhausts to promise significantly different performance, it should be built and tried on the 5AT for comparison with the in-house designed exhausts. Such a practical trial would be the ultimate test of the relative merits of the different exhaust designs, as well as ensuring that the 5AT is equipped with the best of them.