A STEAM LOCOMOTIVE REVIVAL - OR SO MUCH HOT AIR?

Ian MACFARLANE
Department of Aviation
Canberra

ABSTRACT: *This paper discusses the prospects for the revival on Australian railways of the coal-fired steam locomotive, treating the subject in terms of a locomotive that is fully competitive with the modern diesel-electric locomotive.*

The paper quickly reviews the disadvantages of the classic Stephenson-type reciprocating steam locomotive, concluding that only its basic high-performance fire-tube boiler, modified with the proven Porta cyclone gas-producer firebox, is relevant for use on a modern coal-fired locomotive, and that any fresh approach must inevitably start by setting equivalent diesel-electric performance, costs and operating convenience as the absolute minimum for which any steam locomotive project could be commercially justified. A conceptual outline is then given for a universal mixed-traffic Garratt-type, all-bogie, all-adhesion, coal-fired condensing steam turbine-electric locomotive of 5000 kW rating, built entirely within existing technology and operationally equivalent to two modern 2500 kW diesel-electrics; the unit could operate with diesel-electrics in multiple-unit, and run from existing diesel-electric depots with the absolute minimum of extra facilities.

The development and operating costs of such a unit are outlined; and the paper concludes that such a locomotive is a practical and desirable alternative for heavy-duty application on Australian main-line railways where the traffic cannot carry the high capital cost of full electrification.

A technical annex to the paper sets down an outline performance specification for such a locomotive.

A STEAM LOCOMOTIVE REVIVAL - DIESEL OR TESL[1]?

INTRODUCTION

This paper is about the revival of the steam locomotive. It is provocative, because it is meant to be. It is a purely private view, having no official status with railways or Governments although several such bodies have from time to time expressed passing interest, disinterest and even outright hostility to the subject. It does not represent the official views of the IE Aust. or its National Committee on Railway Engineering.

The paper is not about George Stephenson's steam locomotive, whose descendants stirred the imaginations of our fathers as they thrashed heavy freight trains over the mountains, or sped the great expresses of yesteryear a thousand kilometres through the night. Nostalgia has no place in this Forum. And in all countries save those with cheap, abundant coal and low-grade labour, those days and those locomotives have gone forever.

If the paper is none of these things, what is it? It is a framework for further research into a practical locomotive - specifically a turbo-electric steam locomotive - that would once again permit the direct use of Australia's abundant coal reserves on our non-electrified railways. The steam path is the only currently viable option for this (Ref. 1) but in considering steam, it is first necessary briefly to outline in railway operating terms why the classic, Stephenson-type steam locomotive is no longer relevant.

WHY STEAM DISAPPEARED

First, Stephenson's was a lamentably inefficient locomotive, transforming barely 6 percent of its fuel burn into useful work at the wheels. In contrast a modern diesel-electric is about 25 percent efficient in traffic (Table 1) and a modern electric railway is slightly better still. In wasting 94 percent of its fuel the Stephenson locomotive not only created a high direct energy cost; it established a coal fuel-handling and combustion-product pollutant problem some two and a half times worse than it would have been had the basic steam-cycle efficiency been in the broad 15 percent range. Table 1 compares these efficiencies.

Secondly, Stephenson's was an open-cycle steam engine, meaning that it could not easily recover and re-use its feedwater. Some 20 times the volume of water that would have been necessary with a closed-cycle engine therefore had to be located, pumped, treated, stored, fed to and carried on the engine. This massively compounded the problems and costs of water supply and dead tonne-km hauled. All this water passed through the boiler only once; this compounded inherent problems and costs of boiler scaling, washout, wastage and maintenance - even given the advanced water treatment techniques that came in steam's eventide (and they were far from universal).

1 TESL - turbo-electric steam locomotive

Third, the Stephenson locomotive was a reciprocating rigid-chassis machine (steam bogies and direct-drive turbines never really caught on, and the popular Beyer-Garratt solution involved two such reciprocating "engines"). While simple and inherently very reliable, the price of the reciprocating engine was a high inspection and lubrication cost, and very heavy mechanical wear and tear on its long-wheelbase rigid chassis, wheels, and the track. Steam locomotives were purpose-designed, requiring a multiplicity of classes to work the varied traffic tasks, and inflating the cost of spare units and spare parts accordingly.

Fourth, steam was very labour-intensive. Every unit in traffic required a rider attendant to look after each boiler (which meant a two-man crew on every loco) and even with mechanical stokers, skilled firing and handling. These people were backed up by a correspondingly large shed labour force. Few steam locomotives, even those on the handful of railways in the world with hot-water boiler washout and direct re-steaming plants, achieved 30 days between a shed washout lasting at least a day; fewer still achieved 150 000 km between extensive major repairs in shops.

In the later years on the better railways the chassis, and not the boiler, fixed this shopping period. Poor availability resulted in system-wide fleets up to 3 times those of the equivalent diesel electric fleet, and correspondingly large (and physically very heavy) depot, works and supply infrastructures. All these places were likewise very labour-intensive.

Finally, the Stephenson locomotive was an inherently filthy machine. Steam engines in intensive traffic yesterday were very different from those seen on vintage trains today. Steam required an army of people to undertake menial, dirty manual jobs in unpleasant working conditions - jobs that Australian staff disliked by 1950, and simply would not tolerate today. The personal injury rate was high. The trains were dirty. The infrastructure support facilities rapidly degenerated into public eyesores. And steam was an unpleasant neighbour.

Any one of these shortcomings would constitute a fatal flaw to reviving the classic steam locomotive under today's conditions. Their totality made the case for abandoning steam quite unanswerable in Australia thirty years ago; any single shortcoming constitutes a fatal flaw to reviving it in 1983. The analysis in Tables 2 and 3 shows just how poor a financial proposition the Stephenson locomotive would be under today's conditions - and that analysis has been very kind to the classic form of coal-fired railway locomotive. For it ignores environmental and staff problems, as well as the cost of the engine crew, and it assumes the very best US practice and depot equipment, which our railways never had. All these failings must be consciously avoided by a "new" steam locomotive.

THE DIESEL-ELECTRIC LOCOMOTIVE AS A COMPETITOR

In contrast, the modern Australian 6-axle (Co-Co) Diesel Electric Locomotive (DEL) can deliver up to 2 500 kW as soon as its air brake system is pumped up. It can run in coast-to-coast service for 75 000 km before an engine inspection is needed, and achieve 800 000 km between overhauls. Pioneer 1952 model Clyde-GM DEL units are still in operation after running some 6M km over 30 years - over twice as far as the longest-lived steam engines ran in 70 years. The highly flexible DEL can be standardised for mixed-traffic duties, coupled in multiple for operation by a single crew, and remote-radio controlled for mid-train or rear-end operation where draft gear limits and traffic require this. The DEL has an extended speed range dynamic (i.e. rheostatic electric) transmission brake that reduces wheel and brake block wear. On all Australian systems save Queensland and SA, the DEL's major maintenance is concentrated in a few depots, and its main overhaul in one (sometimes two) main works. Turnaround time is limited to fuelling, sanding and safety inspections taking an hour or so. And save perhaps for its engine noise, the diesel-electric locomotive is a good neighbour.

PARAMETERS FOR REPLACING THE DIESEL

For any "new" form of steam locomotive to replace the DEL it must match or improve upon not some but all key elements of the latter's performance, operating convenience and life-cycle cost. The "new" steam locomotive must:

- be able to burn a wide variety of low-grade Australian coals with low calorific values and high ash contents
- be pollution-free in respect of coal-handling, de-ashing, removal of smokebox char and smoke nuisance (which has to include light up and standing, as well as running under partial or full power and coasting downhill)
- be able to operate in multiple unit with standard diesels, as a remote unattended locomotive and, on railways who have had the foresight to fit compatible controls, with electric locomotives as well
- recycle (i.e. condense) its exhaust steam and consume only small (i.e. make-up) volumes of centrally-treated boiler feedwater
- have as high a thermal efficiency as possible.

The above requirements are non-negotiable elements of a performance specification. They require a condensing steam cycle and an unattended boiler fitted with automatic controls (these must provide inbuilt redundancy and 'fail-safe' protection) of the firing, combustion air, feedwater and steam draw off rates, water level, and pressure. All are possible with today's sensor, microprocessor, and boiler technology. But packaging, "tractionising" and proving this unique combination is a formidable development task, especially in the compact and unforgiving environment of railway locomotive.

With a closed feedwater cycle the locomotive should be able to attain at least 60 days and possibly 90 days between de-steaming for boiler washout. Nonetheless:

- an inbuilt capability for frequent short or long periods of unattended "hot layover" is necessary, anywhere on the railway, involving minimum fuel consumption and a readiness to resume duties in no more than (say) 15 min

- infrequent cold starting in the minimum time must be covered. Use of a shore supply is acceptable for start-ups; complex ground-starting equipment or skilled fire-up procedures are not.

Automatic control also becomes necessary for both of these functions.

To match diesel availability all major organs of the "new" steam locomotive must be designed for unit exchange at a major depot in a single shift. This means a totally new engineering approach to the locomotive's steam circuit, and a modular concept for design and repair of all major assemblies, sub-assemblies and components (such a concept also assists development).

The "new" steam locomotive must further:

- match the traction and dynamic braking performance of a DEL of the same mass and axle load

- match or improve upon the relatively low chassis wear rate of the DEL's 3-axle bogies

- be as kind, or kinder, to the track as the DEL

- have uncoupled wheels to permit rapid reprofiling of worn tyres in a pit lathe

These mean 2-axle bogies with individual axle drive. Coupled with previous factors and available technology, they strongly favour an electric transmission, which enables the use of:

- well-accepted alternator/rectifier/dc traction motor technology

- a locomotive with all of its axles driven, i.e. maximum pulling effort

- modern techniques of individual "creep" control of each individual axle, to maximise continuous tractive effort, and achieve a despatch adhesion of at least 25 percent*.

Finally, the "new" steam locomotive must be entirely acceptable to the staff. This means responsiveness to the throttle and brake, predictability and reliability, high standards of cab amenity, safety and

* A locomotive with 100 (force) units of weight, whose design guarantees that the operator can rely on 25 units of pull, has a "despatch adhesion" of 25 percent. For an old DEL it is typically 18 percent, a modern DEL 24-26 percent, and a modern electric unit 28-30 percent.

crashworthiness, and very careful attention to minimising and automating the "dirty" tasks of coaling, de-ashing, char removal and tube cleaning, which must be done away from "clean" tasks performed in the same depots where diesels are maintained.

IMPLICATIONS

The three key elements of the steam prime mover are boiler, engine and condenser. In these departments the overseas protagonists of "new" steam (Refs 2-4) have done their steam-engineering homework well and full credit is due to them. They, too, realise that today's microprocessor can now manage the boiler that only a man could manage previously. But in chasing thermal efficiency and transmission simplicity, they have locked themselves on the reciprocating steam chassis, and thereby created a locomotive concept that is fundamentally unappealing to people running diesel railways. Turbo-electric drive can resolve this impasse and, by isolating the development problems, simplifies development.

Boiler

Several varieties of boiler have been tried on railways but only one type has been made to work consistently well, and that is Robert Stephenson's classic fire-tube boiler with water-wall firebox and induced drafting from the smokebox end. This boiler is compact, reliable, powerful in terms of its mass and, perhaps of surprise to some readers, was typically 70 percent efficient (coal heat to the heat energy in the steam delivered) at rated load. It had a very high short-term peak power output and could be automatically stoked - all of this by 1955. A modified form of cyclone gas-producer firebox, developed by Ing. Porta of the Argentine State Railways in the 1960s and recently re-applied in South Africa, has since eliminated previous problems of smoke nuisance and grate-clinkering. Refined forms of automatic spreader stoker also exist today, as do pneumatic coal-handling systems (industrial boilers and ANL's new bulk-carrier steamships have them). An electric induced draft smokebox fan simplifies draughting control problems.

The cross section of a locomotive is fixed by the loading gauge. The fat, short, deep-firebox Garratt locomotive boiler optimises use of this, and if boiler, engine, and condenser can be separated each can be individually optimised. These considerations favour the "Union-Garratt" concept of a 3-section articulated locomotive with boiler, bunker and coal handling equipment mounted upon a central B section, which is slung between two identical "engine-condenser" sections (i.e. power chassis) A and C. With electric drive, the latter can be all-bogie chassis with all axles driven.

With the condenser mounted on the end chassis the flexible-joint problem reduces to two pairs of compact lines at boiler pressure, one for live steam delivery and, with the feed pump on the engine unit, the other for feedwater return. Bulky exhaust steam lines at condenser vacuum (notorious for leakage problems) are thus eliminated, and high-technology industrial flexibles can be used. The engine unit can provide medium-pressure (about 300 kPa) compressed air for the pneumatic coal-handling system; the usual electrical and air brake flexibles remain.

ENGINE AND AUXILIARIES

Electric transmission, and location of the engine on a separate section from the boiler, combine to confer great flexibility in engine room layout and weight distribution. They also allow the use of a constant-speed turbine as the engine. A turbine eliminates the problem of lubricating reciprocating cylinders, permitting higher superheat temperatures (this promotes efficiency) and avoids the need to separate oil from return feedwater. The constant speed permits optimised blading design and thus turbine efficiency over a wide power output range. It also simplifies the governor, as there is no need to parallel the turbo-alternator sets.

Direct-coupling of turbine to main (traction) alternator permits a compact high-speed alternator, with the option to choose either an ac electric locomotive-type thyristor power control scheme, or to rectify the alternator output and apply a modern DEL-type dc scheme, with proven dc traction motors in either case.

With a single central reduction gearbox (affording one-point engine-room lubrication) each of the following auxiliaries can also be optimised by choice of its speed through its reduction ratio:

- a combination turbo air blower/compressor. This can provide progressive bleed-off for traction motor, cab, engine room and equipment locker ventilation (low pressure); pneumatic coal handling, ash and char purge and unloading (medium pressure); the standard pneumatic brake system, and even air-cycle refrigeration for cab airconditioning (high pressure)
- a constant-delivery turbo feed-pump for the boiler, with simple by-pass control of the feedwater rate
- a condenser cooling (circulation) pump
- the air pump needed for a vacuum condenser

All can be combined on a single modular power block in an optimised engine-room layout.

Choice of an industrial (50 Hz 240/415 V ac) auxiliary electrical system permits:

- ac motors for radiator and smokebox drafting fans and a (cold start) boiler-filling pump, and thus
- use of a mains shore supply alone, for start-up
- conventional oil (distillate) burner, blower, and electric ignition to fire-up the cold boiler
- a regulated constant-frequency supply for the microprocessor
- a reliable source for DEL-compatible 64/80 V dc controls and lighting supply

- while simultaneously eliminating the following sources of high capital cost and/or maintenance:

- auxiliary dc motors and brushgear
- a diesel engine for auxiliary/starting purposes
- main starter motor and ring gears
- batteries
- drive shafts and flexible couplings

The existence of two auxiliary power sources (on Sections A and C) adds to total system reliability, essential for vital services on an unattended boiler. And <u>all</u> reciprocating machines can be totally eliminated from the TESL.

CONDENSER AND RADIATORS

Water-recovery makes a condenser essential on the TESL; thermal efficiency requires a vacuum-condenser steam cycle. Efficiency is maximised with the hottest steam inlet (pressure at least 2 100 kPa, superheat in the 550-600 deg. C range, the latter made possible by a turbine) and the coolest turbine outlet condition, i.e. exhaust into a vacuum of around 15-10 kPa (abs.) at temperatures as close to the maximum ambient (say 50 deg. C) as possible.

Appendix 1 briefly discusses two modern condensing locomotive steam cycles under study overseas:

- the Queen Mary College cycle using a turbo-reheat steam compressor and tubular condenser
- the American Coal Enterprises (ACE) jet-condenser cycle.

The former has a higher cycle efficiency but is more complex and involves a total extra mass of about 8t per end unit; the latter involves a marginally bigger boiler and more exacting detailed radiator design. The important points are that:

- practical cycle options of acceptable efficiency exist
- a basis for financial calculations of 14 percent TESL efficiency, plus 10 percent extra coal for lighting-up and standing, versus 25 percent for diesel, is very conservative.

Table 1 shows that while the diesel engine typically rejects about 25 percent of its fuel burn to radiator water, the TESL cycle rejects 54 percent of a larger fuel burn to condensers and radiators. The radiators on each unit of the TESL will need to reject about 7 MW of heat, cf 1.55 MW for the equivalent diesel's radiators', i.e. about 4.5 times as much. The two W-section lift-out radiator modules in the layout drawing have almost six times the diesel's radiation capacity, showing that this factor is not a limiting problem, even on a very conservative basis. The 60 percent increase of total auxiliary losses reflects the extra parastic loads of condenser circulation and radiator fans.

SPECIFICATION

The above considerations fix one practical form of TESL along the lines of the accompanying outline drawing; obviously there are other arrangements. The individual elements are not particularly novel, but they are all individually proven technologies and their combination into a practical TESL concept is a manageable development task. The rapid development of microprocessor technology over the past few years is central to the practicality of the concept, as is thorough computer modelling of transient load conditions.

Table 3, Note (b) indicates that a pilot fleet of 5.3/4.5 MW TESL units is likely to involve a cost of about $4.2M per locomotive.

OPERATION

The TESL is conceived as a direct operational replacement of the two 2.5/2.25 MW Co-Co diesel-electric units that constitute the current minimum motive power for most heavy-duty main-line passenger, goods and mineral service in Australia (trains have up to six diesel units or three TESL equivalent). Crews would notice no difference between TESL and diesel operation, and either type of locomotive could be driven in multiple from the other, or from a compatible electric locomotive.

DEPOTS

Concerning servicing facilities, a coaling plant must obviously be provided; overhead gravity feed into a bunker sealed by clamshell doors seems appropriate. De-ashing must be automated; as a pneumatic supply is available for coal-handling, the same technique could be used regularly to purge the under-grate ashpan into a separate hopper during the run and dispose of ash into a bunker or closed hopper car at the depot de-ashing point. The traditional technique of having a self-cleaning smokebox blow its char through the stack is environmentally unacceptable nowadays, but much the same technique as that for ashpan purge could be used, with a common disposal hopper and without compromising either clean air or bushfire safety requirements. The drawing shows a practical solution for tube cleaning. Treated water would also be needed, but only at major depots and in the make-up volumes already addressed.

The TESL would be switched to the "hot layover" condition between trips, with one turbine running the auxiliary loads and the other being kept warm by a small steam bleed. Cold starting (infrequent, at major depots only) would use an inbuilt diesel fuel burner fed by an on-board fuel tank (about 1 500 lit) with an external shore supply from the mains, or even another TESL to run burner, blowers, and all controls until the boiler fired up to hot layover in about 4 hours and the onboard systems and coal burners could take over.

Depot examinations would be much the same as those for a DEL, except in respect of the diesel engine which accounts for about half of total DEL maintenance costs. The TESL costs would lie somewhere between diesel and electric costs; DEL costs, plus 10 percent, have been very conservatively assumed. Diesel depots with adequate cranage would be used.

WORKSHOPS

Diesel-electric locomotives are routinely shopped as complete units at typically 800 000 km or at 15 to 20 thousand hour intervals, on the basis of diesel engine overhaul. The TESL has the advantage that its two end units are interchangeable and all its modular components are designed for unit exchange. The complete 3-section locomotive need never be shopped in the main works save after very severe accident damage. Main-works attention to boiler/chassis, turbine equipment components and electrical gear can be completely segregated, and the modular repair tasks contracted out for repair. Railways do not need to re-enter the boiler-shop business, or the unfamiliar field of turbine work.

COSTS

Fuel costs are estimated in Table 2. They show that even the Stephenson form of coal-fired locomotive would today threaten the diesel-electric in terms of fuel costs alone.

Table 3, however, reflects the importance of fleet capital costs at today's interest rates, the heavy labour-dominated component of maintenance costs, and the important influence of high availability for traffic. The figures show why although some African countries are persevering with Stephenson steam units 25-30 years old, Australian railways could not financially contemplate their re-introduction, even if environmental and labour considerations allowed this option.

Table 4 sets out the fleet relativities today, and those likely to exist in 10 years. They show very clearly that

- if the TESL existed as a developed machine today it would already be a very serious threat to the supremacy of the DEL, and that

- fuel cost trends are likely to give TESL traction an advantage in the order of 20-25 percent over diesel-electric traction in 10 years.

THE DEVELOPMENT CHALLENGE

Table 5 sets out a feasible development programme in terms of time and cost, staged to minimise the risks. It is important to stress that every technological element in the above TESL package already exists; what is new is the formidable development challenge of integrating these elements into a proven locomotive system. Estimates err on the generous side for a thorough, low risk development programme, and show that the first two prototype TESL could be running in experimental service by 1988, at a cost of some $A27M. By 1992, for a net decision-to-develop cost of only $40M, we would have a pilot fleet of 10 proven TESL running as a viable alternative option to 20 of today's DEL. And the Australian manufacturing content would be as high as 90 percent.

Such a challenge lies well within the engineering competence of Australia's railways, universities and manufacturing industry. Such a project would need least partial public funding, a genuine interest on the part of at least one railway system with a major interest in coal, and the formation of a project consortium with high-quality management and engineering skills. Australian railways, industry, citizens and Governments should realise not only that this country has all these things, but that we are one of the few countries that has the coal incentive as well. And the developed locomotive would be very exportable - not only to countries with their own coal resources, but to people with neither coal nor indigenous oil, who wish to diversify their transport fuel risks and buy coal fuel from us.

CONCLUSIONS - DIESEL OR TESL?

Analysis has shown that a modern heavy-duty coal-fired turbo-electric steam locomotive is:

- in technical terms, a practical proposition for engineering development
- in railway operational and traffic terms, a practical goal as a one for two diesel replacement
- in financial terms, already competitive with the diesel-electric locomotive, and liable to cost about one-quarter less to operate in a decade
- basically in tune with engineering and economic trends
- as a development option, a staged, low-risk proposition that is thoroughly worthwhile in terms of reducing the cost of rail transport, providing new markets for Australian coal and technology, and increased strategic independence from petroleum-based fuels.

Such a project should appeal to all Australians. If we start on it soon, we could have the prototype running by the 1988 Australian Bicentennial.

References

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Table 1 DERIVATION OF COMPARABLE EFFICIENCIES

"Diesel-equivalent" power rating basis, see line 6

LOCOMOTIVES	DIESEL		STEAM			
Number	(total) 2		Stephenson (2)		TESL (1)	
Type	Diesel Electric Co-Co, 126t		Garratt double 4-10-4		double Bo-Bo-Bo 15t(QR) 21t (others) per axle	
Power, MW each	2.5/2.25		nominal 2.25		5.3/4.5	
	MW	(%)	MW	(%)	MW	(%)
1 FUEL HEAT	12.5	(100)	56.25	(100)	25.7	(100)
Less						
2 Combust, gases and radiation	4.38	(35)	16.9	(30)	6.3	(25)
3 Radiator	3.13	(25)	NA		14.0	(54)
4 GROSS ENGINE OUTPUT	5.0	(40)	NA		5.3	(21)
Less						
5 Auxiliaries	0.5	(4)	NA		0.8	(3)
6 NET INPUT FOR TRACTION	4.5	(36)	4.5	(8)	4.5	(17.5)
Less						
7 Transmission Losses	0.9	(7)	0.28	(0.5)	0.9	(0.4)
8 POWER AT WHEELS	3.6	(29)	4.22	(7.5)	3.6	(14)

EFFICIENCIES

	Diesel	Stephenson	TESL	
Diesel Engine	40	70	75	Boiler
Transmission	80	96	28	Cycle
Locomotive (full-load)	29	11-12	80	Transmission
Fleet overall, traffic	22-27	8-11	14	Fleet[a]
Assumed for study	25	6 and add 10% fuel	14	Assume

Notes on Table 1

a See Appendix 1

NA Not applicable

Table 2 RELATIVE RAILWAY FUEL COSTS[a]

LOCOMOTIVE TYPE			DIESEL	COAL-FIRED STEAM	
				STEPHENSON	TESL
Efficiency, percent (Table 1)			25	6	14
1	Fuel	Type	distillate	coal	
2		Quantity	1000 lit	1 000 kg	
3		Price	36 c/lit[b]	$50/t[c]	
4		Cost, $A	360	50	
5	Heat Content, kWh		10 667	7 108[d]	
6	Useful kWh Output (a)		2 670	426	995
7	Traction Fuel Cost, c/kWh (Output)		13.5	11.7	5.0
8	Add 10 percent for steam light-up, layover etc. costs		-	1.2	0.5
9	Fleet Fuel Cost c/kWh		13.5	12.9	5.5
10	Fleet Fuel Cost Relativities				
	- actual (1983)		100 (base)	96	41
11	- estimated (1992)		180[e]	154[f]	66[f]

Notes on Table 2

a A kWh basis has been used so that readers who need to do so may apply the results to the electrification case as well

b Figure supplied by an Australian railway and representative of 1983

c FOB Export $55, less about $5 port costs, net $50

d 6 110 k cal/kg (11 000 BThU/lb). Typical of low-grade steaming coals

e Estimated real price increase for distillate of 80% over 10 years to 1992

f Estimated real price increase for coal of 60% over 10 years to 1992

Table 3 ESTIMATED FLEET COST RELATIVITIES (1983 AND 1993)

Financial Costs. Crew expense is excluded. $A (1983) throughout

			DIESEL - ELECTRIC	COAL-FIRED STEAM	
				STEPHENSON	TESL
PER LOCO UNIT					
1	Unit size	MW (traction)	2.25	2.25	4.5[a]
2	Unit Cost	$ M	1.4	0.9	4.2[b]
3	Interest @ 12%	$ M pa	0.168	0.108	0.504
4	Depreciation over 30 Years	$ M pa	0.047	0.030	0.140
5	Total Annual Ownership Cost (Items 3+4)	$ M pa	0.215	0.138	0.644
6	Annual Km Run		160 000[c]	80 000[d]	160 000[e]
7	Servicing, Maint., Repair Cost	($/km)	1.25	2.0[f]	2.8[g]
8	Total Annual SMR Cost	$ M pa	0.200	0.160	0.448
9	Annual Fuel Cost	$ M pa (1983)	0.230[h]	0.221[k]	0.187[l]
10	Total Operating cost per loco (5+8+9)	$ M pa	0.645	0.519	1.279
11	(Per-loco, relativities)	(%)	(100)	(80)	(198)
FOR EQUIVALENT FLEETS IN TRAFFIC					
12	Fleet Size (basis 100 diesel units @ 160 000 km pa) (m)		100	200	50
13	Fleet Cost Relativities - 1983 (Item 11 x Item 12, as %)		100	161	99

Notes on Table 3

a One TESL unit replaces two large (double 4-10-4) Garratts or two Co-Co diesel electrics on each train

b TESL capital cost estimated thus for a run of 8 units

	$M
. mechanical parts	1.3
. electric traction and controls	1.5
. Steam elements, complete	1.6
. Total Capital Cost	$M4.2

c Typical of modern Australian diesel main-line practice

d Typical of best previous steam fleet practice (approx. 2-year major shoppings)

e TESL should at least match the diesel by virtue of concept and performance specification

f Estimated to be at least 60% more than equivalent diesel unit per km run. This is kind to the steam locomotive

g Estimated at 10% more for TESL than the two diesels it replaces. This is based on a functional analysis and is conservative for an all-rotary machine with one closed-circuit boiler

h Diesel basis is 4 litres burn @ 36 cents, or $1.44 (Table 2, line 3) per km per unit, over 160 000 km pa, i.e. $230 400 pa

k 96% of diesel (Table 2, line 10) or $221 000 pa

l 41% of diesel (Table 2, line 10) or $94 300 for each of 2 units it replaces, i.e. $187 000

m No allowances are made for spare locomotives. The TESL should need less being totally modularised

Table 4 FLEET TRACTION COST RELATIVITIES[a]

Basis: Percentages of 1983 diesel total

FLEET TYPE	DIESEL - ELECTRIC	COAL-FIRED STEAM	
		STEPHENSON	TESL
1983 Costs			
Ownership	33	43	50
Servicing, Maint., Repairs	31	50	35
Fuel (1983)	36	68	14
1983 Relativities	100	161	99
1992 Costs			
Ownership	33	43	50
Servicing, Maint., Repairs	31	50	35
Fuel[b]	65	109	22
1992 Relativities	139	202	107[c]

Notes on Table 4

a Crew costs, which would heavily penalise the Stephenson steam locomotive, are ignored

b Distillate up 80%, coal up 60% over 10 years (Table 2)

c Overall, a 23% saving

Table 5 A TURBO ELECTRIC STEAM LOCOMOTIVE DEVELOPMENT PROGRAMME

Basis: A three-phase TESL programme involving staged, minimum-risk decisions of design, prototyping and a pilot fleet.

Two prototypes and an initial fleet of at least 10 TESL units would need to run for 5 years in intensive traffic in order to develop and demonstrate the new traction concept to conservative Australian railways.

YEAR START	-	END	PHASE/TASK	COST $M (1983)
			1. DESIGN (Risk $3.0 M)	
0	-	1	Detailed engineering investigation	1.0
1/2	-	2	Detailed design (subcontract)	2.0
				$M 3.0
Year 1 1/2			Decision: proceed to build 2 prototypes	
			2. DEVELOP AND TEST TWO PROTOTYPES (Additional Risk $24m)	
1 1/2	-	2 1/2	Build, develop, and bench-test key steam components	8.0
2	-	3	Construct two prototypes and key spares	12.0
3	-	4 1/2	Field-test prototypes (marginal extra costs)	4.0
				$M 24.0
Year 4			Decision: build pilot fleet of additional 8 TESL	
			3. PROVE AND BUILD FLEET (Additional Risk $41m)	
4 1/2	-	6	Build 8 more locos and spares	35.0
5 1/2	-	6	Modify depot with coal etc facilities	2.0
6	-	7	Operate in traffic (additional engineering costs)	1.0
7	-	8	Fleet modification	3.0
				$M 41.0
TOTALS			TESL project cost - 3 phases	68
			Less cost of 20 diesels (the alternative)	28.0
			Net cost of decision to develop TESL	$M 40.0

STEAM CYCLES FOR "NEW" LOCOMOTIVES — Appendix 1

1. <u>Queen Mary College Cycle</u>. This arises from work by Thring, Sharpe and Le Seur (Refs 2, 5) and uses a separate steam turbo-compressor, driven by the power (turbine) exhaust to reheat the steam between the output of the high-pressure stage and the input to the low-pressure stage. Cycle efficiencies range from over 40 percent to 32 percent depending on steam conditions and with reciprocating drive locomotives, overall efficiencies (coal to wheels) range from 24.5 to 19 percent.

2. <u>American Coal Enterprises, Inc. 'ACE 3000' Cycle</u>. This arises from work in the USA by Porta, Sharpe, Withuhn and Hamilton (of Babcock and Wilcox, Ref. 4). The cycle uses a jet condenser but no published figures can be located; details appear to be proprietary information. The condenser, which works on the "espresso machine" effect, would appear to operate at a higher temperature (probably 70-90 deg C) and calculations suggest a cycle efficiency around 26 percent with a locomotive efficiency of about 16-17 percent (cylinder drive) or about 14 percent for a higher-superheat TESL application.

Previous steam loco efficiencies have been

- Best Stephenson locomotive (Chapelon) about 11 percent.
- 1952 Turbo-electric (non-condensing) about 12 percent,
- The above figures indicate that 14 percent full load thermal efficiency is a conservative target figure.

The concept drawing reflects a jet condenser cycle but if turbo-reheat is used, the engine room is extended by about 1.2m and the cab relocated as a flat-front rather than a low-nose design.