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EVALUATION OF THE YUBA STEAM-ENGINE POWER PLANT

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SUMMARY

Detailed study of the report entitled "Steam Power Package for Military Vehicles - Concept Study" submitted by the Yuba Manaufacturing Company of San Francisco, California, justifies, in the opinion of the writer, a comprehensive testing of the present Yuba tractor and in particular of the power plant. The design and construction of a new power plant for installation in an M-48 tank should proceed simulataneously with the operation of power plants at still higher pressures and temperatures. High-speed, geared steam turbines should be carefully re-evaluated for this type of application. This is an exceedingly worthwhile project and amply justifies all necessary development costs.

OBJECT

The object of this report is to evaluate the Yuba Steam-Engine Power Plant and its possible application to the M-48 tank. The manufacturer submitting the preliminary design for this proposed steam power plant is the Yuba Manufacturing Company of San Francisco, California. This report has been prepared at the request of the Army Ordnance Corps, - Detroit Arsenal, C. H. Richter, Contract Officer.

HISTORICAL

Inasmuch as the proposed Yuba Steam-Engine Power Plant is a high-pressure, high-temperature power plant employing piston engines it is desirable to present a brief history of such plants.

The following excerpt is from p. 175 of Uniflow, Back-Pressure and Steam Extraction Engines (1931) by Eng. Lieut. Com. Thomas Allen, R. N. (S.R.), M. Eng., M. I. Mech. E. The passage applies to the Uniflow steam engine, which is a piston-type engine.

> "The first Uniflow engine appears to have been built by Jacob Perkins and his son at their London iron works in Gray's Inn Road, between 1820 and 1827 during which period Perkins invented both single-acting and compound Uniflow engines utilizing steam pressures up to 1,400 pounds per square inch and steam temperatures up to 1,000°F. Perkins Uniflow engines are subsequently applied in practice, the cut-off being about 12 per cent. Automatic safety devices for the relief of excessive compression were fitted.
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> Locomotive engines embodying the Uniflow principle were built by Rennie and Company subsequent to 1840. These engines were non-condensing and were not a success. The development of the new type of engine was, in fact, retarded by a host of mechanical and lubrication troubles consequent upon the high pressures and temperatures employed, and the Uniflow principle was practically forgotten until the advent of Todd's patent (No. 7031; year 1885)."

On p. 63 of this same book the following will be found: "Back-pressure engines suitable for initial pressures from 450 lbs per sq in. to 1,800 lbs per sq in. have also been designed by the firm of Starke and Hoffman, of Hirschberg (Rsgb), Germany. These engines are shown in Figs. 28 to 30."

The engines shown are heavy-duty types and are constructed in high horsepower ratings. Of course steam generators were available to supply steam at these pressures. For additional valuable data on high-pressure steam engines see Transactions of First and Second World Power Conferences, Steam Engine Sections. The above noted Starke and Hoffman engines used steam up to a temperature of 450°C or 842°F.

The following quotation is taken from Mechanical Engineers' Handbook by Lionel S. Marks (third edition, 1930), p. 1190. The engines described are installed at the Lockland, Ohio, plant of the Philip Carey Manufacturing Company.

> "Power is generated in two 6060 horsepower, five-cylinder, three-crank, triple-expansion vertical engines, directly connected to 3700 kilowatts, alternating-current generators. Steam is supplied to the throttle at 1400 psig and 800°F, total temperature. Steam passes through two single-acting high-pressure cylinders, two single-acting intermediate pressure cylinders, and one double-acting low pressure cylinder, exhausting at 60 psig. Plant designed by W. E. S. Dyer."

The purpose of the preceding brief historical review is to show that the use of high-pressure, highly-superheated steam in piston engines is not of recent origin.

A new central station is under construction at Philo, Ohio, which will supply steam to a steam turbine at 4500 psig and 1150°F total temperature.

EVALUATION OF THE PRACTICABILITY OF THE YUBA STEAM-ENGINE POWER PLANT FOR THE M-48 TANK

It is appropriate here to quote some facts and test data pertaining to the power plant in the White steam motor car. The following is quoted from Applied Thermodynamics for Engineers by William D. Ennis, (first edition; 1910):

> "A result of exceptional interest was obtained in Carpenter's tests ["Steam Plant of the White Motorcar" by R. C. Carpenter, ASME Transactions, Volume XXVIII, 2,225; also p. 579] of the engines of the White steam motor car. The maximum output was only 45 horsepower, the weight of the entire power plant only 643 pounds. The engine was cross-compound, running condensing. The boiler pressure ranged up to 595 psig, with as much as 300°F of superheat; the exhaust from the engine was, in fact, superheated. A steam-rate as low as 10.8 pounds was obtained, or of 12 pounds per brake horsepower, corresponding to 246 Btu per brake-horsepower per minute."

This corresponds to a brake thermal efficiency of 17.2 percent. The foregoing data are useful for comparative purposes. The writer is familiar with the performance of the White steam car in the interval 1908-1911 and can state that it had many fine operating characteristics, such as very smooth operation and great ease of control. These characteristics were also inherent in other early steam automobiles: Locomobile; Mobile; Stanley, and Toledo. The writer had personal experience with all of these. The limitations of the early steam automobiles are well known. However, modern metallurgical developments and improved manufacturing methods permit the use of much higher pressures and temperatures than were previously possible and make it necessary to re-evaluate the steam power plant as applied to automotive uses. Such a re-evaluation brings out many outstanding advantages of steam propulsion as applied to automotive uses. This discussion is here primarily concerned with the Yuba Steam-Engine Power Plant as applied to the M-48 tank.

The adoption of a relatively high-pressure and high-temperature steam supply as indicated in the report referred to in the Summary above is strictly sound, thermodynamically, and contributes greatly to the efficiency of the steam cycle.

It is noted in the Yuba Report that the pressure normally used in their steam tractor was 1500 psi but that one of their engines was modified somewhat and operated at pressures in excess of 2000 psi. Under these conditions of operation it is noted that "it has been difficult to obtain reproducible results." The steam temperatures at the throttle are not noted but are presumably high. The selection of steam pressures and temperatures by the Yuba Company for use in their proposed plant is important in view of their accumulated experience. However, the use of steam pressures well above the critical pressure of 3206.2 psia for steam should be carefully reviewed together with the use of the highest possible steam temperatures. The absence of any latent heat effect at or above the critical pressure, the absence of any steam bubble formation, the somewhat improved coefficients of heat transfer, and the increased thermodynamic cyclic efficiency are points of much importance. The above statements are made with a full knowledge of the difficulties involved.

The application of extremely-high-speed, geared-type steam turbines should also be critcally reviewed in the light of new metallurgical developments.

The Yuba Steam Generator

The Yuba steam generator is well designed. Like all flash-type steam generators, it is subject to rapid scaling of the tubes and resultant tube failures by overheating if raw feedwater is used. However, with a complete, absolutely tight condensing system and with no entry of oil from the engines into the condensate there will be no appreciable tube fouling and the tubes should maintain their original high rates of heat transfer indefinitely. It is highly essential to keep oil out of the steam generator to the greatest extent possible. The discussion given in the Yuba Report of the method used to cope with this oil problem is of great importance and on the basis of their discussion it appears that they are satisfied with their treatment of this problem. Basically, however, a prime mover requiring no lubrication, such as a steam turbine, would be highly desirable.

When this power plant is used in temperatures below 32°F, the problem of freezing up during idle periods is one of the outstanding difficulties. However, although difficult, the problem is surmountable; even the starting of internal combustion engines under very low temperature conditions has always been a real problem, and aside from the provisions necessary to prevent freeze-ups, the starting problems of this type of steam power plant present no particular difficulties.

The Yuba feedwater pump is an interesting design utilizing twelve small, single-acting plunger pumps. As noted, the purpose of this multicylinder feed-pump is to furnish the same amount of water to all steam-generator tubes. It is suggested here that careful consideration be given to the use of a much simpler pump supplying feedwater to a single manifold which in turn is connected to each steam-generator tube by means of an accurately designed flow-nozzle which will assure a uniform delivery of feedwater to each steam-generator tube. Uniform delivery of feedwater to each tube is dependent entirely upon the tightness of the pump suction and discharge valves and upon the tightness of the packing surrounding the pump plungers. It is not apparent from drawing N-T 105 that the pump plunger packing assembly is readily accessible for adjustment and replacement. The whole power plant is entirely dependent upon the feedwater pumping system and this must have the maximum of reliability in operation and must be readily accessible for inspection, adjustments, repairs, and replacements. Suction and discharge valves are vital elements and the foregoing requirements also apply to these valves. It is highly desirable to minimize the number of parts in the feed-pump to the greatest extent possible.

In order to keep oxygen out of the system and thus to minimize corrosion and electrolytic action of all metals involved, the feedwater supply should at all times be retained in an entirely closed system and not be exposed to air. The Yuba Plant accomplishes this.

There is no question about the safety of the Yuba steam generator and this is, of course, a point of great importance for this type of power plant. Ability to burn practically all available liquid fuels is another highly valuable feature. Fuel oils and heavy distillates, because of their lower first cost, great availability, and substantial reduction of fire and explosion hazards, are highly desirable fuels.

The design of the Yuba steam generator is very good. However, the the number of mechanical joints in the steam-generator tubing system should be reduced to the greatest extent possible. This is just a basic design requirement applying to all steam-generators of the general type. The incorporation in the Yuba steam-generator of water-cooled combustion-chamber walls, high-velocity convection heat transfer, large heat transfer surfaces, an economizer section, and air-preheater represents the use of every possible modern feature contributing to the success of high-efficiency, high-capacity steam generators.

The Yuba Steam Engine

At the outset it is well to state that the four-engine arrangement is distinctly preferable to the two-engine arrangement. The Yuba engine shows that great care and skill have been used in its design, together with previously accumulated experience in steam-tractor operation and design. The high-torque characteristic of steam engines when operating with late cut-offs is very valuable. Also the fact that the full stalling torque is available with no steam flow is a highly valuable feature. These two features of the steam engine are largely responsible for the many years of unchallenged supremacy of the steam locomotive. In tank operation these two features have tremendous significance.

The Yuba engine incorporates the very best features in the design of small, high-speed, high-pressure, high-temperature steam engines. High steam pressures and temperatures necessitate the use of poppet-type steam admission and exhaust valves. Single-acting cylinders fitted with trunk pistons eliminate the high pressure piston-rod packing problems always present with double-acting steam engines which are particularly troublesome in the case of high-pressure, high-temperature steam engines.

It is well to note here some of the piston-ring problems which are inherent in high-pressure, high-temperature steam engines and which may be very troublesome and cause high maintenance expense. It is a known fact that it is much more difficult to lubricate satisfactorily a high-pressure, high-temperature steam engine than to lubricate a heavy-duty Diesel engine, or any other internal combustion engine for that matter. The reasons for this are that although the maximum temperatures existing in say, a Diesel-engine cylinder may be of the order of 4200° to 4400°F, the cylinder-wall temperature rarely exceeds about 450°F because of the cooling effect of the water jackets. In the case of engines using steam of, say, 1000°F, the cylinder-wall temperature during the admission portion of the stroke, while not attaining 1000°F, is well above the temperature at which most lubricating oils will carbonize (about 600° to 650°F) and there is a continual, slow breaking down of the lubricating oil and the release of free carbon, usually in a somewhat sticky form which can foul piston-rings, valves, and heat-transfer surfaces in both the steam-generator and condenser systems. This can be minimized by proper piston and piston-ring design and the proper selection of cylinder oils. Another thing to be recognized in high-pressure, high-temperature steam engines is that during admission, the steam is at its maximum temperature and with a late cut-off there is a very severe lubricating problem. Also, the duty imposed on the piston rings is very heavy and can easily lead to the building up of pressures behind the first one or two piston rings to such a value that the lubricating oil film is ruptured and metallic contact between the cylinder-wall, piston, and piston-rings ensues, producing rapid wear and scoring of these parts. This has been and still is a very severe and troublesome group of problems in the design, construction, and operation of high-pressure, high-temperature steam engines. Drawing NT-400 indicates that the leakage of steam along the admission-valve stems into the crank-case is reduced as much as possible by the only practicable method, namely, by the use of annular grooves, (Ramsbottom Grooves) machined out of the valve-stems. These grooves, in reality, are a form of labyrinth packing. Note, however, that a labyrinth packing of any type is not and cannot be a perfectly steam-tight packing. It will always pass some steam. A designer can reduce the steam leakage to some acceptably low value but can never completely eliminate it by this means. It should also be noted that these admission-valve stems must run without lubrication because of the high temperatures existing at their hot ends.

The designers of the Yuba engine clearly recognize this problem of unavoidable steam leakage and its subsequent mixing of condensate with the lubricating oil, and have provided means for as complete removal of the condensate from the lubricating oil as possible. They state that this is satisfactorily accomplished with their equipment.

The reasons given by the Yuba Company for the adoption of a four-cylinder engine are entirely justified. The thermodynamic analyses of steam engine efficiencies and other related items have been carefully studied and checked in representative places and the various analyses given are sound and well presented.

The Yuba Steam Condensers and Fans

The steam condensers and fans are vital to the operation of this power plant. The condensing of the steam and reclamation of the condensate for feedwater are absolutely essential. Whatever moderate vacua are available in cold weather together with the resultant increase in thermodynamic efficiency is of minor importance compared with the reclamation of the condensate for feedwater. It is obvious that thermodynamic efficiency is reduced as the back-pressure against which the engines exhaust increases. The extent of this back-pressure is a function of the load carried by the power plant and the ambient temperature of the atmosphere. Whenever the size of a condenser must be limited, the low heat-transfer rates of air-cooled steam condensers make it necessary to allow much higher temperature differentials between the steam within the condenser and the air outside than in the case of conventional water-cooled steam condensers. In the case under consideration, the size must be held within very definite limits. It is important to note that for any given assigned back-pressure, its effect on the thermodynamic efficiency becomes less, percentagewise, as the initial steam pressure and temperature are increased. The condensers should always be designed for cleaning as easily as possible.

Some thought should perhaps be given to flooding the condensers with raw water so as to assist their performance in extreme conditions by means of evaporative cooling. This would of course involve a raw-water supply tank and a power-driven, centrifugal circulating water pump and minor accessories. The fan equipment is well selected and well adapted to this particular application.

General Discussion

This "Concept Study" of a "Steam Power Package for Military Vehicles" as submitted by the Yuba Manufacturing Company has been carefully studied. It is a well presented report covering the thermodynamic theory and analysis, design, and expected performance.

It is the carefully considered opinion of the writer that the Army Ordnance Corps - Detroit Arsenal is well justified in proceeding at once with the construction of a steam power plant for use in the M-48 tank as submitted by the Yuba Manufacturing Company. This does not imply that the present designs as submitted are to be considered as the final design. However, the present design, it is confidently believed, will produce an installation which will be generally satisfactory and will lead to rapid improvements and refinements in design and operation. Coincident with the construction of this installation, extensive research and testing should proceed along the lines of utilizing higher steam pressures and temperatures, investigating the possibilities of driving with very high speed, geared steam turbines of special types, determination of engine wear and engine life, etc. In fact, the layout of a testing program is a feature requiring much care and planning and is beyond the scope of this report.

It is believed that the Yuba Power Plant as proposed in the "Concept Study" could be constructed and installed in a tank ready for testing in 12 to 18 months. The writer is fully aware that it is quite hazardous to make this sort of a prediction with little or no knowledge of the shop facilities for this type of work; however, from knowledge of similar development work the above opinion seems reasonable.

THERMODYNAMIC EFFICIENCY OF STEAM AND OTHER POWER PLANT CYCLES

The only important power-plant cycles available for use in tank power plants are steam cycles and internal-combustion cycles and these are the only ones that will be considered here. It is important to note the highest thermal efficiencies that are being attained in power plants operating on these cycles. The highest presently attainable thermal efficiencies for spark-ignition, internal-combustion engines in large ratings is about 38 percent based on shaft horsepower. The highest presently attainable thermal efficiency for Diesel engines is about 41 to 42 percent based on shaft horsepower and is realized by high-horsepower, low-speed, marine-type Diesel engines. In the case of the most modern central stations, the highest overall thermal efficiency from the coal pile to the alternator terminals is about 35 percent, although some new plants under construction are expected to have an overall efficiency of between 36 and 37 percent. Some new plants now in the design stage and under consideration are aiming at overall thermal efficiency from the coal pile to the generator terminals in the range from 38 to 40 percent.

In the case of the steam cycles, (as against internal combustion cycles) as applied to engines suitable for tank propulsion, it can be stated that while the brake thermal efficiencies of very-high-pressure, high-temperature steam engines would be somewhat below those for internal combustion engines, nevertheless the difference would not be the sole determining factor in the selection of the steam type of power plant. It is interesting to note what thermodynamic efficiency theoretically possible for a steam engine operating on the ideal Rankine Cycle for the following assumed conditions:

Pressure of steam at throttle	=	5000 psia
Temperature of steam at throttle	=	1200°F
Pressure of steam at engine exhaust	=	20 psia or 5.3 psig
Theoretical thermal efficiency	=	39.6 percent

Note that this is the theoretical cycle efficiency and not the actual thermal efficiency based on shaft horsepower. After considering the many factors involved it appears reasonable to expect that the average thermodynamic efficiency, based on shaft horsepower, will average from 5 percent at the best to about 10 percent at the worst below corresponding internal-combustion-engine efficiencies. When the use of much cheaper fuel is taken into account and other desirable characteristics are evaluated, the actual net cost of operation can and will be much less in the case of the steam power plant. The present time is much more favorable for the development of high-pressure, high-temperature steam power plants than at any time in the past. Metallurgical developments in particular have made many new alloys available, automatic control components have been developed to high degrees of durability and reliability, and the air-cooled condenser which has for so long been considered incapable of further improvement has very recently been developed to a point where its performance is superior in many cases to that of evaporative-type condensers. This is the new "UNICON" condenser and is made by the Kramer-Trenton Company of Trenton, New Jersey. A recent article concerning this air-cooled condenser has been written by Otto J. Nussbaum, Chief Engineer, Kramer-Trenton Company and is entitled "Adaptability of

Air-Cooled Condensers for Large Tonnage Systems" (Refrigerating Engineering, March, 1954). Although this article is concerned with the performance of air-cooled refrigerant condensers, the same general discussion will apply to air-cooled steam condensers. The performance characteristics of these condensers should be investigated to determine their suitability for possible use in the Yuba Steam Power Plant.

Testing of the present tractor and particularly the testing of its power plant should proceed at once to determine comprehensive performance data; these data should be used to assist in the design of a new power plant for installation in an M-48 tank. This new design should proceed simultaneously with the testing as noted above. The testing program should also include the operation of plants at still higher pressures and temperatures and the determination of their performance characteristics.

This is an exceedingly worthwhile project and amply justifies all necessary development costs.