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Coal-Fueled Diesel Locomotive Test

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CONTRACT INFORMATION

Contract Number DE-AC21-88MC23174

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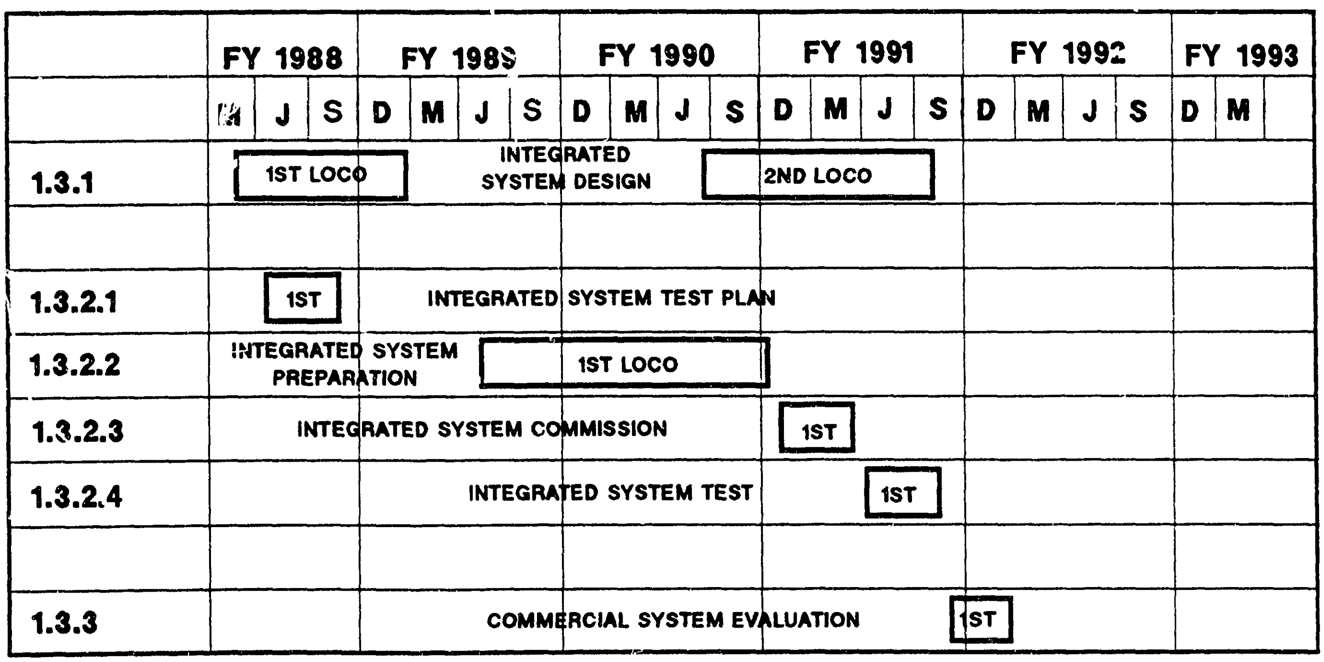
Schedule and Milestones

Coal-Fueled Diesel Technology Development
Integrated Systems Phase



OBJECTIVES

Overall Project

GE Transportation Systems has been investigating coal/water slurry (CWS) as a fuel for diesel-electric locomotives under contract to the U.S. Department of Energy (Morgantown Energy Technology Center), sponsored in part by Norfolk Southern Corp., Pennsylvania Energy Development Authority, and New York Energy Research and Development Authority. Demonstrating the coal-fueled diesel engine in its actual operating environment, a locomotive, was the principal objective of the Integrated Systems phase of this project. An existing oil-fueled diesel locomotive was to be converted in two stages during this phase, the final nearly emulating the concept for a commercial coal-fueled diesel locomotive [1].

Stage I Locomotive

The first stage coal-fueled diesel locomotive testing was primarily developmental in nature, not predominantly the verification test that the second stage would be. Therefore, the main thrust of the first stage coal-fueled diesel locomotive testing was to verify that the various engine support and control systems functioned as required, gaining operational experience and identifying problems [2]. Testing of this coal-fueled diesel locomotive culminated with operation on the GE Transportation Systems test track in Erie during the 4th quarter of 1991.

BACKGROUND INFORMATION

Coal-Fueled Diesel Locomotive Development

GE has been involved in the research and development of a coal-fueled diesel engine and locomotive since 1983. Early economic studies showed that moderate crude oil prices could generate enough fuel cost savings to justify the investment in hardware and infrastructure associated with burning CWS in a locomotive [3]. The biggest challenges to the development of a commercially-acceptable coal-fueled diesel-electric locomotive are integrating all systems into a working unit that can be operated in railroad service. This involves mainly the following three systems: (1) the multi-cylinder coal-fueled diesel engine, (2) the locomotive and engine controls, and (3) the CWS fuel supply system.

Consequently, a workable 12-cylinder coal-fueled diesel engine was considered necessary at this stage to evolve the required locomotive support systems, in addition to gaining valuable multi-cylinder engine operating experience. The first 12-cylinder coal-fueled diesel engine was operated successfully in the GE-TS diesel engine laboratory at Erie during 1990, completing 10 test hours of running on CWS, at up to 1860 kW at 1050 rev/min.

Coal/Water Slurry Characteristics

The CWS fuel used during this project was obtained from Otisca, Inc. (Syracuse, NY). It was prepared from micronized and de-ashed Kentucky Blue Gem coal to 49.0% coal loading by weight, with less than 1% ash and 5 micron mean diameter particle size. Its higher heating value was analyzed at approximately 34630 kJ/kg. Anti-agglomerating additive Triton X-114 was added to the CWS at GE Transportation Systems at 2% of coal weight.

The nature of the Otisca CWS fuel makes it inherently more difficult to store, pump, and inject than diesel fuel, since concepts which govern Newtonian or normally viscous liquids do not apply entirely to CWS. Otisca CWS tends to be unstable and to settle in tanks and lines after a period of time, making it necessary to provide a means of agitation during storage. To avoid long-term settling problems and to minimize losses, piping velocities were designed to be in the 60-90 m/min range.

PROJECT DESCRIPTION

Coal-Fueled Diesel Locomotive

Overview. A GE Transportation Systems engineering test locomotive, GE 607, was to be modified for use with both locomotive development stages. GE 607 is a model C39-8--a microprocessor-controlled, six-axle locomotive, having motor-driven blowers, radiator fans, and air compressor. The first stage 12-cylinder coal-fueled diesel engine was installed in this locomotive during the 2nd quarter of 1991, after completion of testing in the GE diesel engine laboratory.

The 12-cylinder coal-fueled diesel engine replaced the original 16-cylinder oil-fueled diesel engine on GE 607, which allowed space to house the extra equipment needed for the CWS fuel supply and coal-fueled diesel engine support systems. After the first stage coal-fueled diesel engine was installed, the locomotive was subsequently renumbered to GE 609, as the first coal-fueled diesel locomotive. Locomotive testing included both stationary testing and running on the GE Transportation Systems Erie test track.

The engine controls, for pilot-to-slurry transitioning and overspeed protection, were applied to the locomotive, though no attempt was made at this stage to incorporate them into the locomotive microprocessor. A remote control station for the CWS fuel system was installed in the locomotive operators cab, with the main control cabinet on the tender.

The first stage coal-fueled diesel locomotive testing included a fuel tender car coupled to its rear, see Fig. 1. The tender served as a testbed for working with the CWS; having a separate fuel tender car facilitated testing to study problems related to CWS mixing, long-term storage, freezing, and variations in coal loading within a large tank. The CWS handling systems were thoroughly tested prior to the installation of the coal-fueled diesel engine on the locomotive.

CWS is supplied to the locomotive from the tender, along with purge water. (See Fig. 2 for an isometric line drawing of the locomotive piping). A tube-in-shell heat exchanger (where CWS flows through the tubes and the shell side contains thermostatically-controlled water) maintains the temperature of the CWS supplied to the engine charge pump. A strainer is also located on the locomotive before the engine

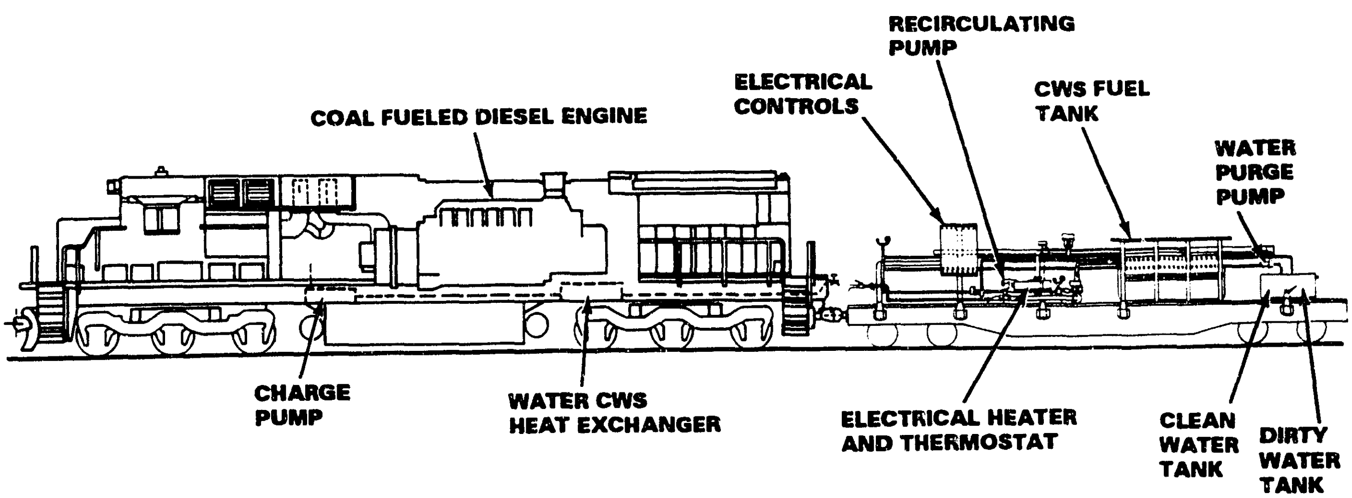


Figure 1. Stage I Coal-Fueled Diesel Locomotive and Tender Configuration

charge pump to filter any larger contaminants in the CWS fuel supply. (A 28 mesh screen filter is used to filter dirt and coagulated CWS lumps, a smaller mesh would drive the pressure drop up too high and eventually filter out the desired coal).

The CWS is supplied to the engine header by a progressing-cavity charge pump. An orifice in the header provides back-pressure to the engine charge pump, which is maintained constant by variable-speed motor controls with header pressure feedback. The progressing-cavity charge pump distributes up to 72 L/min of CWS at 2.8 MPa to all of the piston isolation pumps atop the engine cylinders. This pump is specifically designed for difficult pumping applications like this--abrasive, high-pressure CWS. The major disadvantage of the pump is its great length, which requires it to be mounted on top of the locomotive fuel tank; no other location on the locomotive could accommodate its over 6-m length.

Coal-Fueled Diesel Engine. The first stage 12-cylinder coal-fueled diesel engine is a modified GE-Transportation Systems model 7FDL diesel engine, with a standard full-load rating of 2240 kW at 1050 rev/min. It is a 4-stroke compression-ignition engine of 229 mm cylinder bore and 267 mm piston stroke. The first stage 12-cylinder coal-fueled diesel engine

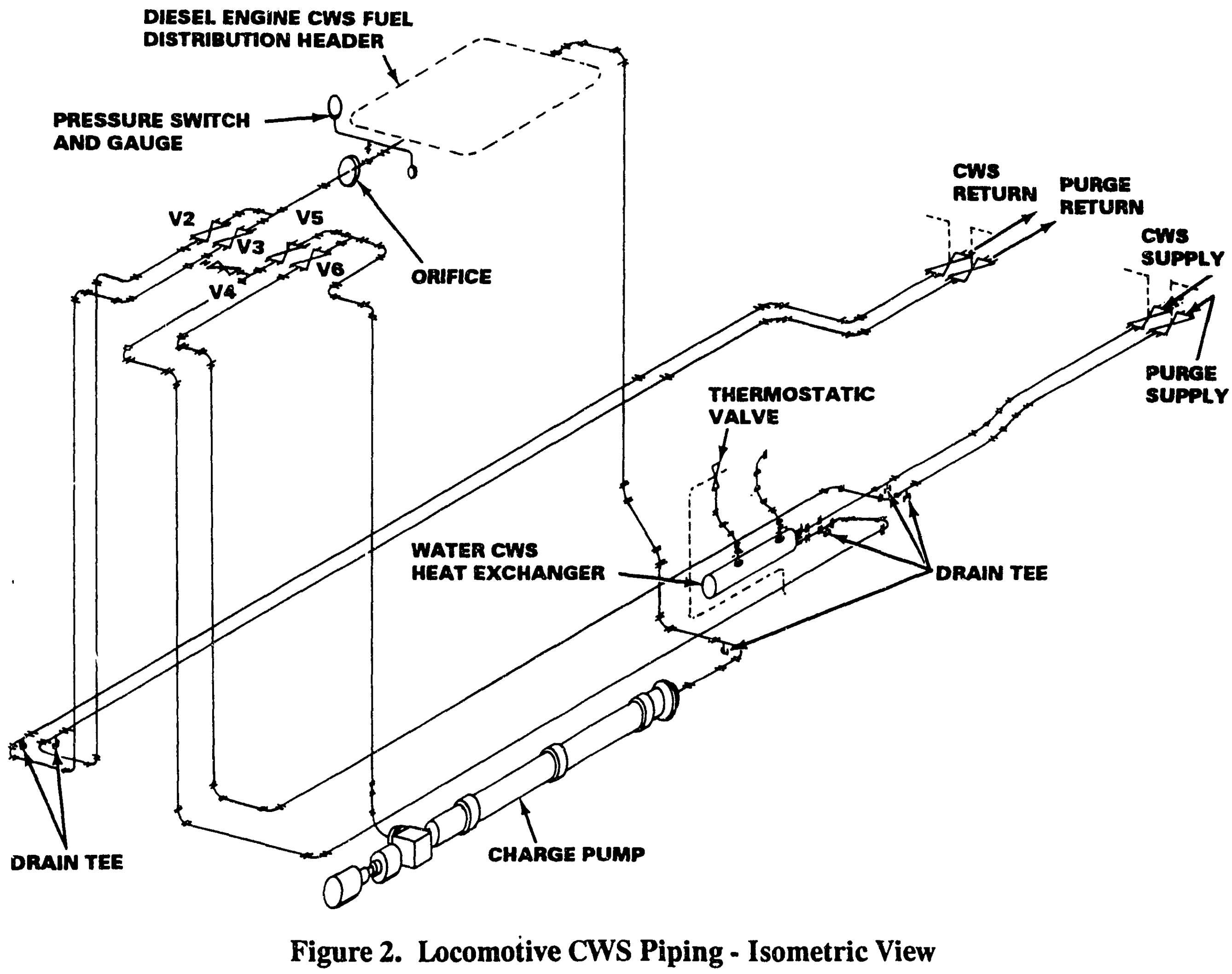


Figure 2. Locomotive CWS Piping - Isometric View

began by modifying a standard diesel engine with dual positive-displacement fuel injection systems, see Fig. 3. This includes two sets of mechanical jerk pumps, piston isolation pumps, and twin positive displacement fuel injectors, with a modified fuel-rack linkage [4].

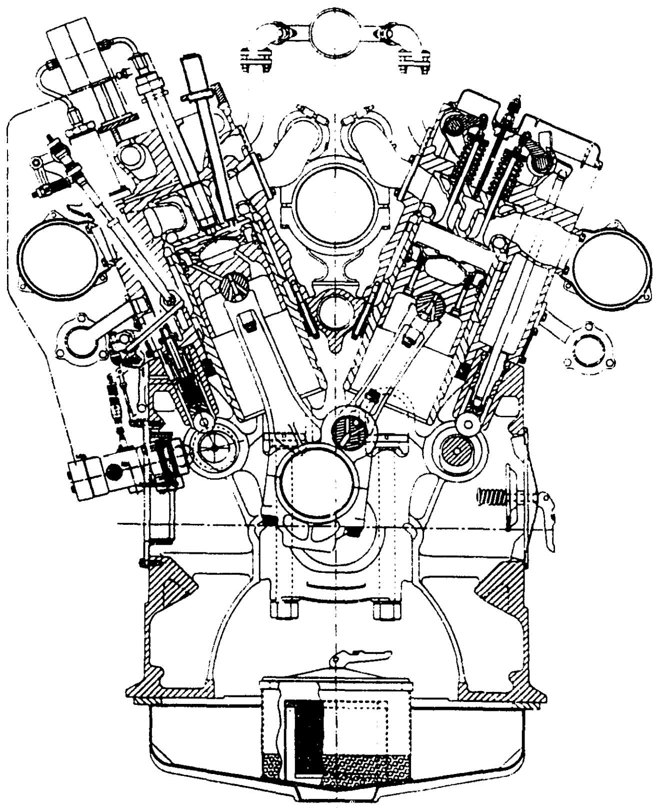


Figure 3. Stage I Coal-Fueled Diesel Engine Cross-Section Layout

The CWS fuel injection system is used exclusively at higher power levels (locomotive throttle positions N4-N8). This positive-displacement design has the capability to provide the full-load CWS fuel quantity required for each cylinder. A larger-than-standard main injector is centrally-mounted in each cylinder head.

The pilot fuel injection system was developed to provide both the small amount of diesel fuel needed at high power, to enhance coal combustion, and also the large amount for starting and lower power running (idle through N4), where there is no CWS injection. Each pilot injector is mounted off-center in the cylinder head, spraying from the side.

A unique governor-modulated fuel-rack linkage controls the amount of both CWS and diesel fuel injected into the cylinders on the 12-cylinder coal-fueled diesel engine. The linkage synchronizes both CWS and pilot jerk pumps on all twelve cylinders during start up, acceleration on diesel fuel, transition to coal combustion, and high power running on CWS. Additionally, a remote-controlled electric linear actuator on each bank is provided to decrease the amounts of diesel fuel added to the cylinders during coal combustion.

Coal-Water Slurry Fuel Tender

The fuel tender uses a railroad flatcar to carry the tanks, pumps, valves, and associated controls for the first stage locomotive CWS fuel system. Having a separate fuel tender car behind the locomotive facilitated testing to study problems related to CWS handling, allowing the flexibility and easy access necessary for experimentation and repiping. Techniques developed on this testbed were to be incorporated into the second stage locomotive.

The CWS fuel system consists of two piping loops, see Fig. 4. The primary piping loop is used to recirculate the CWS within the CWS fuel tank. The CWS is recirculated to prevent coal from settling out of the mixture in the tank. It draws from a floating suction line within the tank, where the CWS will be less concentrated, and returns through two perforated lines across the bottom of the tank, where the CWS will be more concentrated.

The CWS recirculation pump is rated at 360 L/min and 350 kPa. Originally, this was a lobe-type pump driven by a 7.5 kW motor, with a variable speed capability. A double-diaphragm air-operated pump of the same capacity and discharge pressure ratings

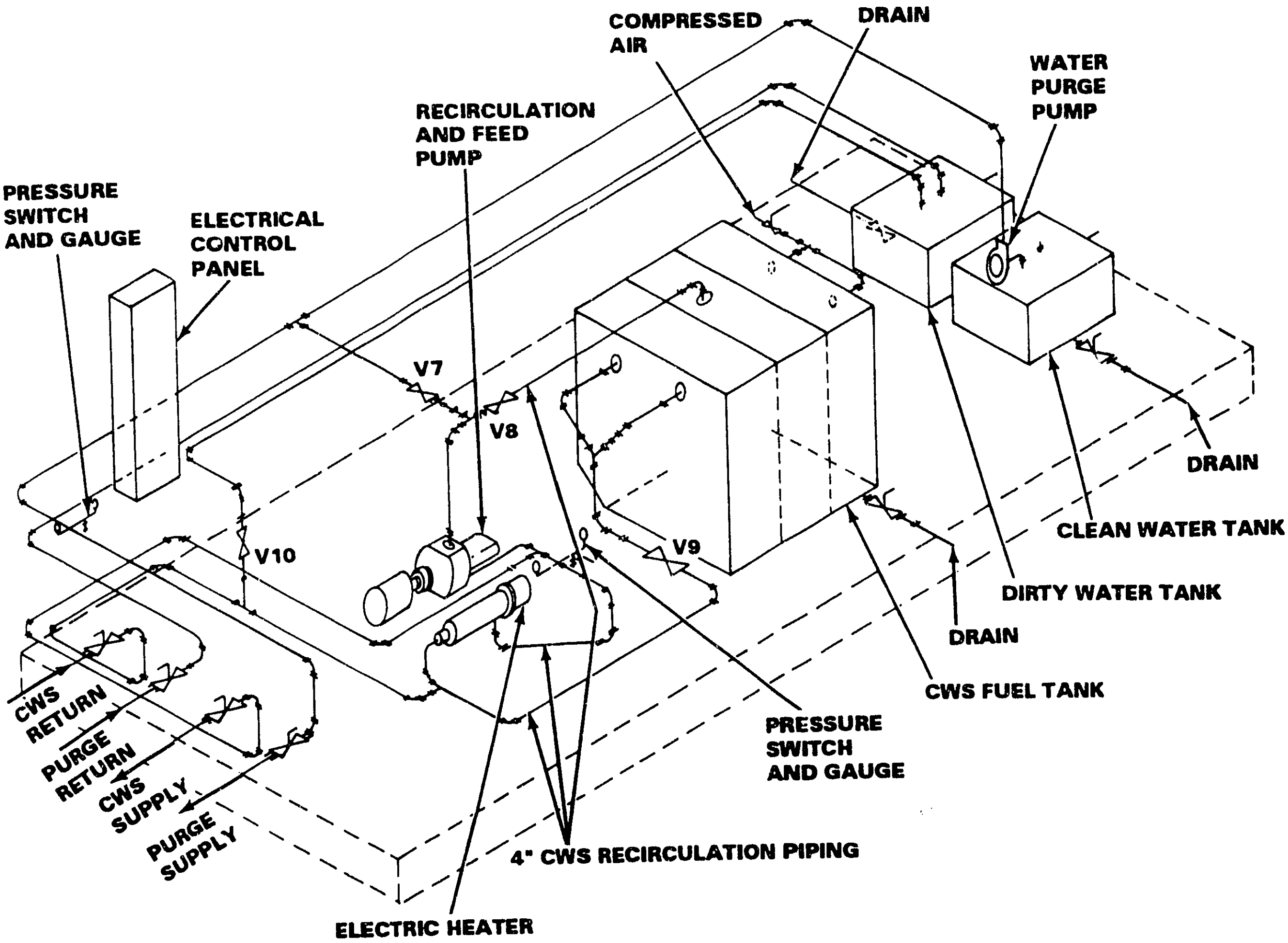


Figure 4. Tender CWS Piping (Original) - Isometric View

replaced this pump when it proved unreliable in pumping the CWS. The recirculation pump initially also supplied CWS to the locomotive.

The secondary piping loop supplies CWS to the locomotive and the engine charge pump through hoses connecting the tender to the locomotive. Control valves on the locomotive determine whether the CWS is supplied to the engine charge pump or is circulated back to the tender. A separate, smaller (72 L/min at 350 kPa) air-driven, double-diaphragm pump was later employed to feed the locomotive circulation loop.

The main electrical control cabinet for CWS fuel system is located on the tender car. Besides controlling the two CWS fuel system piping loops described above by relay logic for valve actuation, the electrical control cabinet also contains relays for water purge system. The controls are operated by a manual selector switch with following positions: (1) charge locomotive circulation, (2) charge engine header, (3) run engine, (4) purge engine header, (5) locomotive circulation standby, and (6) purge locomotive circulation. (See Results--Systems Operations for a description of the CWS fuel system state at each position).

A nominal 3800-L tank holds the CWS fuel used on the coal-fueled diesel locomotive. The CWS fuel tank is essentially one quarter segment of a full size 15,000-L locomotive fuel tank. (This was done to minimize problems when scaling up in size for the second stage locomotive). In addition, it has removable top hatches and baffles, to allow for modifications during testing not possible if it were in the standard locomotive fuel tank location. Two 50 mm diameter recirculation tubes, with 8 mm holes, spaced 100 mm apart, and angled 30 degrees downward, run along the bottom of the tank. Two compressed air bubbling lines, 25 mm in diameter, with horizontal 3 mm holes, 100 mm apart, are also in the bottom of the tank to keep the CWS agitated if recirculation fails.

An electric circulation heater with internal thermostat was used in the CWS fuel tank recirculation line to prevent freezing of the CWS during low ambient temperatures. This heater was a pass-through type, with several individual elements, allowing the CWS flow to be thoroughly heated. It was originally rated at 5 kW; this was later up-rated to 18 kW for use without insulating the CWS fuel tank. Later still, it was removed altogether due to the internal clogging that occurred whenever it heated the CWS.

When the engine is not running on CWS for long periods of time, it is necessary to flush the CWS system with clean water; the CWS piping must be either purged or drained to prevent the coal particles from settling out of the slurry. There are a number of valves, controlled to provide the proper timing and sequencing, two purge water tanks, and a centrifugal purge water pump, rated at 36 L/min and 350 kPa for this purpose. Water, from the 380-L clean water tank at the rear of the tender, is pumped through the piping and equipment to flush the remaining CWS into the 380-L dirty water tank, also at the rear of the tender. Drain valves, located throughout the tender and locomotive, enable the piping to be drained if they cannot be purged for some reason.

Test Car

During the track tests, The GE Transportation Systems test car, a converted railroad passenger car with extensive on-board instrumentation and computer systems, continuously monitors performance of the engine and locomotive. Recorded data includes engine load, speed, temperatures and pressures, see Table 1. Instrumentation used for testing is a reduced set-up from the Diesel Engine Laboratory, using a Hewlett Packard model 3852S data acquisition and control unit, but also involved the use of a 386 PC and LabWindows software.

Table 1. Recorded Test Parameters

Description	Range
Engine speed	0 to 1200 rpm
Turbocharger speed	0 to 21,000 rpm
Ambient air temp.	0 to 50 ^{o}C
Engine H_2O out temp.	10 to 120 ^{o}C
Engine oil out temp.	10 to 120 ^{o}C
Manifold air temp.	0 to 120 ^{o}C
Pre-turbine temp.	10 to 650 ^{o}C
Diesel fuel temp.	5 to 50 ^{o}C
CWS fuel temp.	5 to 50 ^{o}C
Pilot fuel rack	0 to 30 mm
CWS fuel rack	0 to 30 mm
Barometric press.	70 to 105 kPa
Manifold air press.	0 to 270 kPa
Pre-turbine press.	0 to 270 kPa
Lube oil header press.	0 to 800 kPa
Rectifier DC voltage	0 to 1200 V
Rectifier DC current	0 to 10000 A
Elapsed time	sec

An engine-generator set, located on the test car, provides 60 Hz AC power to the CWS pumps and electrical equipment. This was necessary because AC motors were used to ease selection of pumps and the locomotive

AC power is not available at 60 Hz. CWS fuel system pump motors and equipment would be replaced with DC for the second stage coal-fueled diesel locomotive.

RESULTS

Systems Operations

Preparation. The CWS tank recirculation loop is always operating to ensure the coal remains in suspension in the CWS fuel. The engine is started and warmed up in a normal fashion until the lube oil reaches 80°C. The CWS fuel system controls are then stepped through the consecutive states of the system described below. (Refer to the CWS fuel system schematic shown in Fig. 5).

Charge Locomotive Circulation (1). The feed pump is started to initiate the charging of the locomotive CWS piping. Purge water left in the locomotive circulation piping is cleared by pumping CWS from the CWS fuel tank. (Valves V4, V8, V10 only are open). When all purge water has been pushed into the dirty water tank on the tender, CWS is routed back into the CWS tank (by closing V10 and opening V9). The feed pump continues recirculating CWS from the tank through the locomotive. All this is generally done before starting a test track run.

Charge Engine Header (2). The engine charge pump is started at slow speed. The charge pump then pumps the CWS through

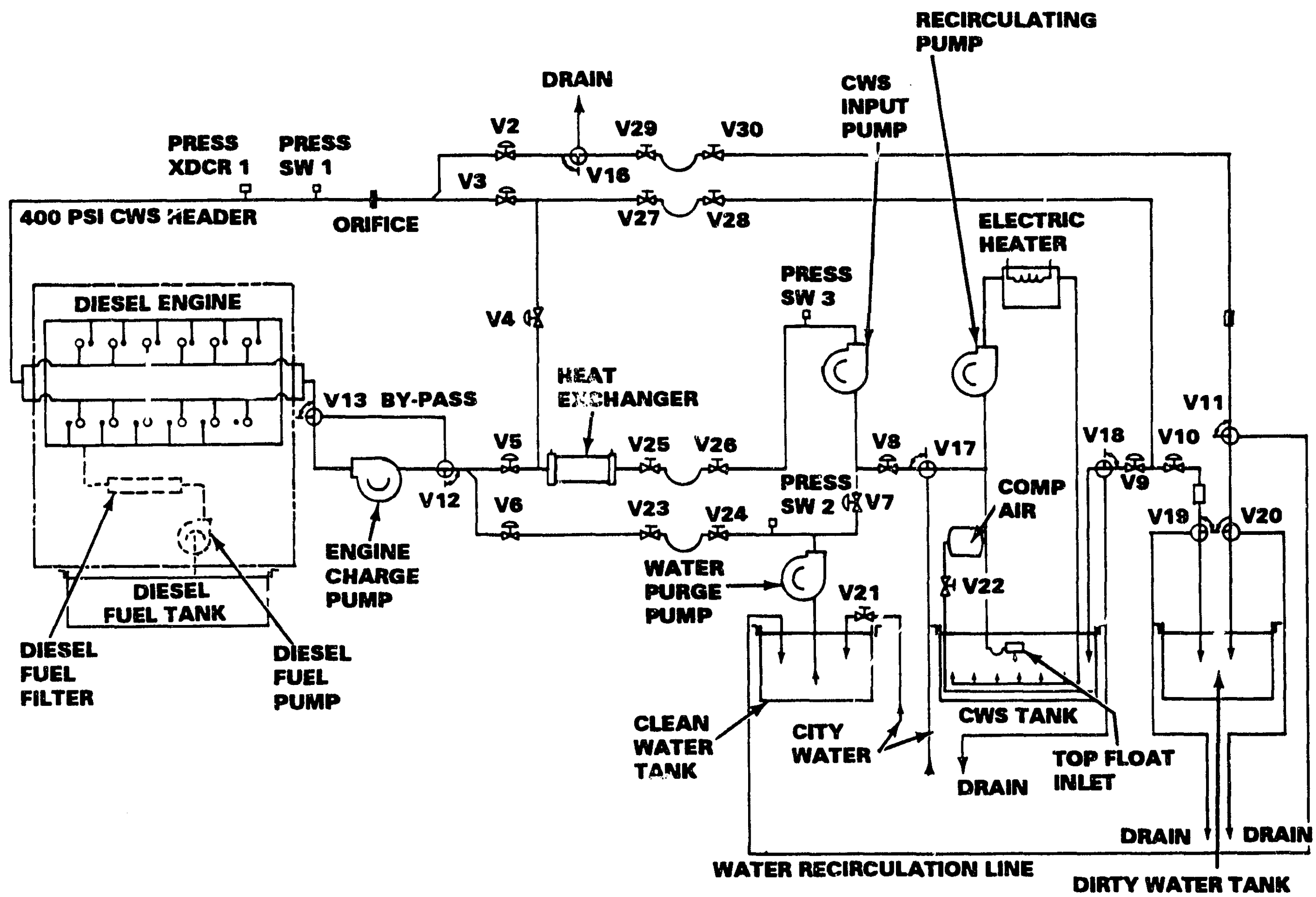


Figure 5. Modified CWS Fuel System Schematic

the engine header pushing purge water out into the dirty water tank. (Valves V3, V5, V8, V10 are open; V4 and V9 are now closed). When all the purge water has been pushed into the dirty water tank, CWS is re-routed from the engine header back to the CWS tank where it is recirculated (by opening V10 and closing V9 again). This is all done as the locomotive starts its test track run.

Run Engine (3). The engine charge pump is run at high speed to feed CWS to the engine CWS fuel injection system. Feedback from a pressure transducer mounted near the orifice is used to control pump speed to maintain a CWS pressure of 2.8 MPa at the engine. During this state, the locomotive will be running on CWS.

Transition into running on CWS fuel begins by increasing the throttle to N4 (600 kW at 880 rev/min). One linear rack actuator is retracted to decrease the diesel fuel injected on that cylinder bank. At this point, the engine governor attempts to compensate for the lower diesel fuel delivery by increasing the CWS fuel injection. After the governor stabilizes, the other actuator is retracted--the engine will now be running on CWS, see Fig. 6. (For the first stage coal-fueled diesel locomotive test track runs, the average times observed during transition in the GE Transportation Systems diesel engine laboratory testing were used to determine when and how fast to retract the actuators, rather than observing the engine cylinder exhaust temperatures as in the lab).

Transition out of running on CWS fuel is done by returning the throttle to N4, then extending both rack actuators simultaneously. At full extension, the engine is returned to running solely on diesel fuel. The locomotive throttle is now decreased to N3 (300 kW at 880 rev/min) and the CWS fuel injectors are purged with water during the next state.

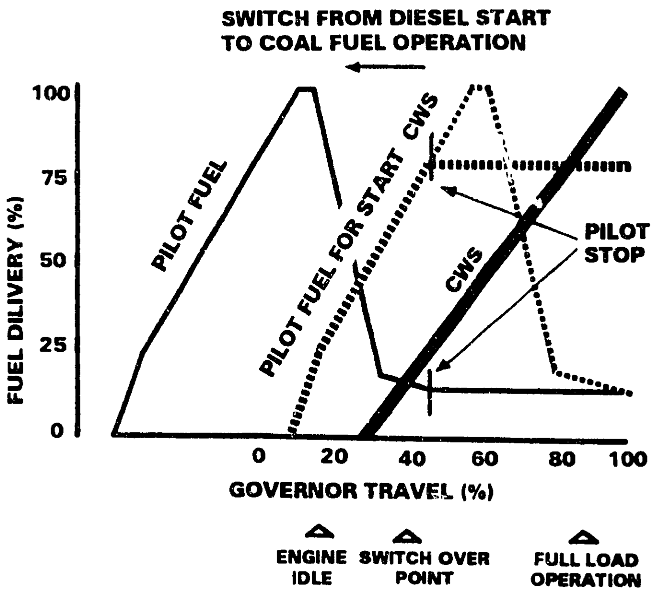


Figure 6. Diesel & CWS Fuel Delivery Rates

Purge Engine Header (4). The engine charge pump is returned to low speed and the purge water pump is started. This routes water from the clean water tank through the engine header to the dirty water tank. CWS in the engine will be pushed into the dirty water tank. (Valves V2, V4, V6, V8, V9 are all open; V3 and V5 are now closed). When the engine purge is complete, the purge water and engine charge pumps are stopped.

Locomotive Circulation Stand-By (5). The feed pump continues to circulate CWS through the locomotive while the engine runs on diesel fuel alone. At this state there is an option to either return to the Charge Engine Header state (2) or go on to the next state.

Purge Locomotive Circulation (6). The purge water pump is now restarted to pump water from the clean water tank through the locomotive circulation lines. (Valves V4, V7, V9 are open; V2, V6, V8 are now closed). Prior to the complete purging of the CWS, the purge water is routed into the dirty water tank from the CWS tank (by opening V10 and closing V9). When all lines have been purged, the purge water pump is stopped; only the CWS fuel tank recirculation is operating at this point.

Operating Summary

Stationary Testing. The coal-fueled diesel engine was run on CWS July 25, 1991 for the first time since being installed on the locomotive. The locomotive was run in self-load up to throttle position N6 (1500 kW at 1050 rev/min). (Self-load is where the dynamic-braking resistor grids are used to dissipate the engine power as heat). This first run was successful in the locomotive self-load test, but the purge water circuit did not operated properly, so that the CWS fuel injectors and piston pumps were clogged with coal. The second test, on August 22, was not as successful due to CWS dilution during testing. A third attempt to run the locomotive in self-load on September 12 was not successful at all.

Since CWS dilution occurred during testing, the timing of the valves in the locomotive CWS supply and purge water piping was re-checked. Second, the engine fuel-rack linkage needed to be set for correct conditions at throttle position N4 to transition properly. Third, because there were now four air-driven pumps (for the engine backing fluid and purge oil plus the CWS recirculation and feed pumps), air consumption exceeded the capacity of the locomotive air compressor. For the duration of the first stage locomotive testing, another locomotive was used to supply the additional compressed air required.

After the above corrections were made, a final self-load test of the locomotive was run on October 22. This test was successful in making the transitions both into and out of coal combustion and purging the CWS fuel injectors prior to shutdown. Since the engine now functioned as it had in the lab, preparations were made to begin test track running.

Test Track Running. The GE Transportation Systems test track starts at the southeastern edge of the Erie plant and runs east for about 4 miles. For a test track run two diesel-electric locomotives, operating in dynamic braking mode, were used as load units for the coal-fueled diesel locomotive (GE 609) to simulate a trailing train.

On November 12, 1991, the first track run was attempted, but was unsuccessful due to a wide pressure fluctuations in the engine CWS header pressure. It was found that the feed pump was starving the engine charge pump because its air shuttle valve was sticking. This was corrected and Friday, November 15 marked the first successful run of the coal-fueled diesel locomotive on the test track.

A demonstration run was then scheduled for our sponsors on November 20. However, for some reason four CWS fuel injectors stuck their needles early in the run, two of which stuck open. Consequently, the engine died in the middle of transition, causing all the CWS fuel injectors to clog with coal.

A final locomotive track test was run on December 12. This test was partially successful, running on CWS for about 5 minutes. Again, a steady CWS header pressure could not be maintained, so that the CWS running had to be stopped before reaching the end of the test track. It may be that since the charge pump was now leaking CWS out of its shaft seal while running, and quite a lot, it could not hold the engine header pressure required to run on CWS for any length of time. Or there could have been such a build-up of coal in the locomotive piping, due to improper flushing (requiring more water to flush than anticipated), that the engine charge pump was starving, since this coal build-up was actually observed in the CWS piping during tear-down.

Discussion. Normally, the coal-fueled diesel engine is started and run in the lower throttle positions (N1-N3) using the pilot diesel fuel, then the CWS will gradually be introduced. This process requires smooth throttle changes both upward and downward. It was found during testing, however, that the auxiliary loads cause a tremendous change in the governor modulation, and thus the fuel-rack linkage. The auxiliary loads were then set to be either full on or off during transition into CWS running for first stage. This would need to be resolved during the controls integration of second stage locomotive.

FUTURE WORK

Stage II Engine Test

For first stage coal-fueled diesel engine and locomotive testing, the pilot system was mechanically linked to the main system. The pilot system will change to an electrically-operated one for the second stage coal-fueled diesel engine. The engine will also be modified to convert the CWS fuel injection system to an accumulator-type system. (See Ref. 5 for a description of the accumulator- type CWS fuel injection system). Thus, the second stage coal-fueled diesel engine will then have dual electronic fuel injection systems.

Stage II Locomotive Test

The second stage coal-fueled diesel locomotive would be the prototype for commercialization and would have many improvements developed over the course of this project. The primary modifications involve the engine, fuel tank, and emissions control system. (Fig. 7 illustrates the second stage/commercial concept coal-fueled diesel locomotive). The next generation coal-fueled

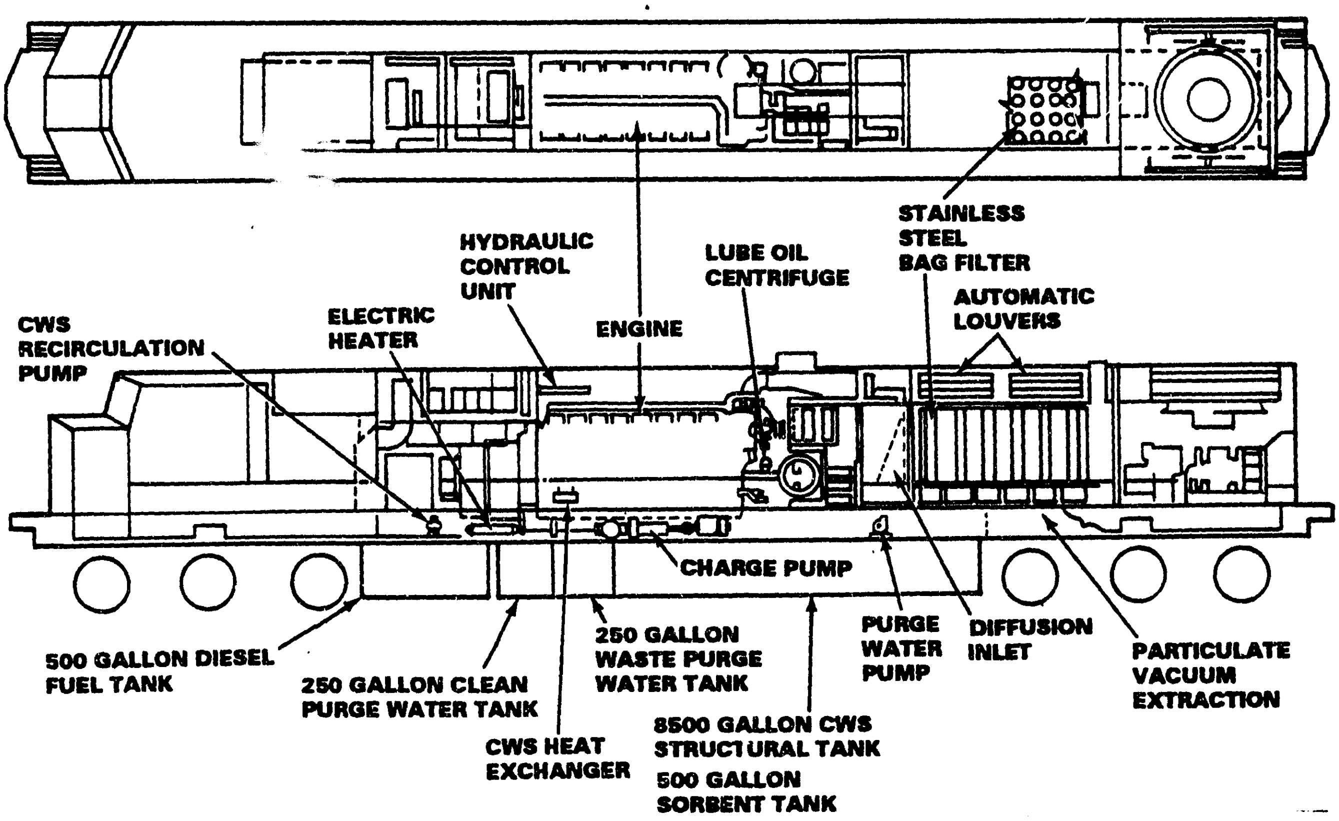


Figure 7. Stage II/Concept Coal-Fueled Diesel Locomotive

diesel engine, described above, would be installed in the locomotive. The overall length of the locomotive would increase in order to accommodate an emission control system on-board. A new, larger fuel tank, segmented for CWS, diesel fuel, and purge water, would be designed for the second stage locomotive, eliminating the need for a tender. Space would also be available for the recirculation and purge water pumps, and associated piping, to be relocated from the tender. Additionally, the coal-fueled diesel engine and CWS fuel system controls would be integrated into the locomotive's microprocessor control system. Locomotive testing would again include both stationary testing and runs on the test track, plus limited running on a commercial railroad.

However, this second coal-fueled diesel locomotive will not be built during the course of this project, due to two accentuating factors. One is reductions in the federal budget for alternate fuels programs. The other is lower oil prices, which preclude any near-term commercialization of this technology. Hence, GE-Transportation Systems and the U.S. Department of Energy (Morgantown Energy Technology Center) have agreed to conclude this project in an orderly manner, without proceeding into the second stage locomotive work.

REFERENCES

[1] Hsu, B.D., A.K. Kalafala, and C.S. Cook. 1991. Coal-Fueled Diesel Locomotives Overview. **Proceedings of the 8th Annual Coal-Fueled Heat Engines and Gas Stream Cleanup Systems Contractors Review Meeting**, ed. W.H. Webb, R.C. Bedick, D.W. Geiling, and D.C. Cicero, pp. 72-80. DOE/METC-91/6122. NTIS/DE91002091. Springfield, VA: National Technical Information Service.

[2] GE Transportation Systems. 1989. **Integrated System Design Report.** DOE/MC/23174-3068. NTIS/DE92001149. Springfield, VA: National Technical Information Service.

[3] Hapeman, M.J., and S.D. Savkar. 1986. **Economic Assessment of Coal Burning Diesel Locomotives.** 86-ICE-14. New York, NY: American Society of Mechanical Engineers.

[4] McDowell, R.E., S.L. Basic, and G.L. Confer. 1991. Proof-of-Concept Testing of a Medium Speed 12-Cylinder Coal-Fueled Diesel Engine. **Proceedings of the 8th Annual Coal-Fueled Heat Engines and Gas Stream Cleanup Systems Contractors Review Meeting**, ed. W.H. Webb, R.C. Bedick, D.W. Geiling, and D.C. Cicero, pp. 314-326. DOE/METC-91/6122. NTIS/DE91002091. Springfield, VA: National Technical Information Service.

[5] Hsu, B.D. 1989. Coal Fueled Diesel Technology Development: GE Single Cylinder Engine Results. **Proceedings of the 6th Annual Coal-Fueled Heat Engines and Gas Stream Cleanup Systems Contractors Review Meeting**, ed. R.C. Bedick, R.P. Dorchak, N.F. Rekos, and W.H. Webb, pp. 169-175. DOE/METC-89/6101. NTIS/DE89000952. Springfield, VA: National Technical Information Service.

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