are repeatedly operated from idle to full torque, full speed, and with either propane or natural gas, certainly shows that the jet system will fire regularly over a wide range of operating conditions.

**Future of Jet-Ignition System**

Concluding this presentation we think it is appropriate to take a look into the crystal ball for hints as to the possible future of the jet-ignition system. First, the already established good performance of jet ignition in a-c generating plants opens a new field for reducing fuel cost. In areas where gas is readily available it no longer will be necessary to use both liquid and gas fuels to retain the high efficiencies afforded by diesel compression ratios. In fact, even in areas where the gas supply may be interrupted temporarily, propane could be used as a standby in these emergencies and thereby eliminate the continual need for relatively expensive liquid fuel. Many installations now pay thousands of dollars each year for diesel fuel required by dual-fuel engines just to protect against a gas interruption. Experience has shown that these interruptions usually average not more than two days each winter. Jet ignition with simple propane standby facilities should handle this situation nicely.

**Economic Considerations.** As to economics, the jet-ignition system in this particular installation showed a 19 per cent reduction in fuel cost as compared to the same engine operating on the dual-fuel cycle using liquid pilot oil for ignition.

**Additional Spark Models Installed**

To illustrate further the combustion regularity and the over-all reliability of the jet-ignition system, several additional $8\times10$ OP spark models have been installed in other municipal generating plants. All of these units are maintaining the necessary accurate speed control over the complete load range. The first of these new production installations logged over 7500 hr during its first 11 months of operation, and 7500 hr in 11 months means pretty continuous service.

As previously mentioned the jet-ignition principle also was applied to the FM $5\times7$, OP gas engine. Fig. 9 shows the small $5\times7$ equipped with a pulse generator and coils for jet ignition. The first spark-fired small OP's were all applied to oil-field drilling rigs. The No. 1 rig installation has now been in service approximately 7500 hr and has completed the 16th hole ranging between 7000 and 8000 ft in depth. The rig operated on either propane or natural gas. Oil-field-drilling service, in which engines

Finally, jet ignition's already established fine performance with propane fuel makes it feasible to consider spark-fired high-compression gas engines for mobile equipment such as switching locomotives, towboats, and so on. The thought of propane locomotives becomes even more intriguing when one considers the current emphasis on smoke abatement.

A new approach to the old problem of operating spark-ignition engines on a high-compression cycle was made with jet ignition. The result was not only an engine with diesel compression but one which did not need any of the traditional carburetion controls so long associated with spark engines. That engines using the jet system measure up to being reliable, stable, and versatile is evident in the field records.

**Discussion**

E. G. Beardsley. This discusser believes that the engineers of every company who have built, or are now building, large two-cycle gas engines have at one time or another made an effort to improve the regularity of firing these engines at partial loads.

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It is quite probable that many of them have come up with a similar idea to that which is presented in this paper, although the actual execution in the form of a mechanical design may have been somewhat different.

Two engineers working for this discussers company did have this same idea working entirely independently a short time after they attacked the problem. In other words, if the engines misfire at partial loads due to the mixture being too lean why not divide off part of the combustion chamber so that when enough gas is injected into the small chamber to operate the engine at no load, only enough air will be present to give a good firing mixture?

Fig. 10 shows the first design that we built and tested. This was installed on a horizontal 16 X 20 single-cylinder gas-engine-driven compressor unit. The light load firing was remarkably good but the head unfortunately developed a crack in it and the project was abandoned as there was not sufficient interest to carry on further work at that time.

Fig. 11 shows another approach to this problem, this head having been installed in 1940 on a model RA 14 X 14 angle-type gas-engine-driven compressor unit. The light load firing was remarkably good but the head unfortunately developed a crack in it and the project was abandoned as there was not sufficient interest to carry on further work at that time.

Fig. 12 shows another design which was installed on an engine in 1941. This gave extremely good results on a single-cylinder unit, but was not as good on a multicyle engine presumably because of uneven air distribution and scavenging which always occurs on the multicyle engine to some extent.

The three combustion chambers described in the foregoing were used with low compression cylinders. The compression pressure was about 110 psi in each case. The percents of total combustion-chamber volume in each case were 12 per cent, 6.5, and 16 per cent, respectively.

One will notice that on all three designs a small gas-injection valve and a spark plug are provided in the auxiliary chamber as well as the main injection valve in the main part of the chamber. This project was abandoned because of the press of war work and although work on other methods of improving light load firing have been investigated and some adopted, this project was never taken up again.

The authors are to be complimented on their paper and on the work which they have done on this project.

W. R. Crooks. The authors, Thompson, Beadle, and Blake are to be complimented for obtaining and reporting on, a simple solution for a difficult problem. The Cooper-Bessemer Corporation has done extensive work along this line, with comparable results. The conventional two-cycle gas engine, whether it be low compression—100 psig, medium compression—250 psig, or diesel compression—from 400 psig up, is known to tend to miss at light loads due to the extremely lean air-fuel mixture. The jet ignition presumably supplies the extra energy required to ignite the lean mixtures at part loads.

It seems likely that engines operating with this type of ignition will have the same type of difficulty we encountered in the early days of gas-diesel operation. For a short period of time we operated the gas-diesel, or dual-fuel engines with the same amount of air we use for diesel operation. As the load decreased, the air-fuel ratio became increasingly leaner until the limits of inflammability were reached which agree with the results the authors have reported.

With the pilot fuel set at 10 per cent of the total full-load fuel, we obtained the following one-quarter load performance: (a) High pilot fuel-oil requirements to ignite the very lean mixtures. (b) High gas fuel consumption. (c) Objectionable exhaust odors. The exhaust gases were obnoxious from the odors of aldehydes and were sufficiently strong to irritate the mucous membranes of the noses of persons in the vicinity of the engine operation. It appears as if the combustion was so slow in some portions of the cylinder that combustion never proceeded beyond the "cold-flame" stage of combustion before it was discharged into the exhaust. It would seem as if these conditions would prevail with jet-ignited partial-load operation of two-cycle engines.
A. W. Hussmann. It may be of interest to note that the very same idea of jet ignition has been in the air for quite some time in connection with the gasoline Otto-engine. We have the same problem of misfiring for lean mixtures in our cars. There we provide for the proper air-fuel ratio by throttling the air for part loads. This throttling is very wasteful and is, to a large extent, responsible for the shamefully poor fuel economy. We are putting more and more horsepower in our cars with the result that we are always working with throttling in the uneconomical part-load range.

The jet-ignition system seems to be one answer to the problem of how to operate our spark-ignition engines without air throttling, i.e., with good part-load economy. With fuel admission by carburation, this was not practicable. However, with the advent of gasoline injection, the idea seems to be highly promising. And it is more than just an idea. Promising test results have been published by Prof. J. J. Broeze of Delft, Holland, and Prof. W. E. Meyer of The Pennsylvania State University has done some preliminary testing with an unthrottled gasoline-injection engine with most encouraging results. Here is definitely a field where further research and development are needed.

W. K. Newcomb. This interesting paper tells how a difficult problem was solved. The auxiliary combustion chamber or cell where an easily ignitable gas and air mixture is maintained is a very ingenious device. If it permits smooth operation at part loads, it has greatly improved the flexibility of a type of engine where modulation of the air is difficult and not very successful.

Four-cycle engines, on the other hand, are inherently easy to control and their smoothness of operation and flexibility are well known. With naturally aspirated four-cycle spark-ignition engines the constant-quality mixing valve is simple and reliable. With turbocharged four-cycle engines the air control is also simple. Here the speed of the exhaust-gas-driven supercharger responds to the load and this raises or lowers the manifold air pressure. However, we find this control is not enough and also use a butterfly valve which is positioned by the air or gas pressure. With a centrifugal blower we can do this without having to blow off any air because the blower operates farther back on its characteristic curve.

The authors imply that air modulation improves the fuel consumption at part loads. It would be interesting to know what part-load fuel consumption they get without air modulation.

Table 1 mentions 53:1 air-fuel ratio. This sounds more like total air-to-fuel ratio without allowance for scavenging. How were this and other mixture ratios measured?

AUTHORS’ CLOSURE

We certainly appreciate the fine discussions and wish to thank the discussers for their interest and efforts spent in the preparation of their comments.

Mr. Beardsley’s experiences with low-compression gas engines utilizing divided combustion chambers is quite interesting. His basic experiments parallel our early work in being directed toward enrichment of a small section of the trapped combustion charge. This is added evidence that the principles involved in the jet-ignition combustion system are not limited to any one engine. The engine details between the two programs vary widely but their reactions toward improved light-load operation with the local enrichment are similar.

Mr. Crooks implies that he would expect the operation at light loads to be erratic regardless of the ignition system. The air supply is not reduced below that required for the same engine operating as a diesel oil engine. We definitely disagree with this in the case of our dual-fuel and spark-ignition engines which both use the same air as their diesel counterpart. We have never reached a pilot-fuel limit below which combustion became irregular in the dual-fuel engine, but rather are limited on pilot-fuel quantity by the least amount we can meter consistently. Jet ignition gave consistent and regular ignition throughout the entire speed and load range. Air modulation or reduction controls are optional where reducing the light-load fuel consumption is important.

Objectionable exhaust smells have never been reported around the engines although none has been applied in tightly enclosed applications such as mines.

Professor Hussmann’s comments regarding the application of jet-ignition principles in gasoline engines further points out the widening of the field of potential applications for the jet-combustion system.

Mr. Newcomb requests clarification of the method for determining the stated air-fuel ratios and for the values of part-load fuel consumptions on spark-ignition gas operation when the air supply is not reduced.

The air-fuel ratios were determined on a per cycle basis using the pounds of air trapped in the cylinder at air-port closing divided by the pounds of fuel used per cycle. The 50 per cent rated-load fuel consumption without air modulation for the larger opposed-piston engine is approximately 12 per cent above that obtained with reduced air.

Dr. Elliot raised questions on lean charges, adjustments for propane and natural gas, odor in exhaust gases, and light-load operation of dual-fuel and spark-fired gas engines, while making an eloquent plea for more complete data from development programs.

By “firing of lean charges” we mean obtaining a regular combustion cycle with the lean charges. As he indicates, unburned gases are present after combustion of these charges. The burning of these unburned gases is the major source of reduced fuel consumption with reduced air, which is optional, when operation at these loads is prolonged.

The fuel consumption on a Btu basis is very close on propane and natural gas. Owing to the differences in the specific heating values, this results in lower gas-system operating pressures at all points when using propane. The energy released by the cell is very close for both fuels.

Exhaust odor is treated in the comments on Mr. Crook’s discussion. Light-load combustion with full air is stable with both dual fuel and jet ignition. It was the knowledge that the pilot oil regularly ignited these extremely lean mixtures that spurred on the jet-ignition development.