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THE WEBSTER-HEISE VALVE:

A SIGNIFICANT IMPROVEMENT IN THE INTERNAL COMBUSTION ENGINE AND ITS FUELS?

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ABSTRACT

The efficiency of internal combustion engines has long been limited by the problems associated with fuel preparation and distribution. A new valve technology has been developed which may reduce or eliminate some of those problems. The Webster-Heise valve apparently causes gasoline and other auto fuels to vaporize at low engine temperatures and to mix with incoming air. Preliminary testing suggests potential for major oil conservation, increases in available torque, improvements in fuel economy, and major reductions in lead and other additives and in automotive pollutants such as nitrogen oxides, carbon monoxide, and unburned hydrocarbons. The valve also appears to reduce engine octane requirements by 10 to 15 points. Additional testing will be necessary to fully evaluate its potential.

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I. PREFACE

This report is an analysis of the concept, technology, and hardware of a new valve to increase engine efficiency that has been developed by the Webster-Heise Corporation. The methodology used in this report consists of a discussion of the attempts to improve internal combustion, a physical description of the Webster-Heise valve and its operation, a history of the development of the valve, the current status of the device, the outlook for its possible acceptance, and its potential impact on various issues of national concern. The Appendix consists of a more detailed analysis of the nature of the existing problems in current production systems, the theoretical reasons for these problems, and their theoretical solutions as related to the Webster-Heise valve. In addition, a summary of tests is provided so that the reader will have relevant data on which to base his own conclusions. The technical analysis (Appendix I) is a system approach (from carburetor to tailpipe) explaining the effects of the valve upon different aspects of combustion (before, during, and after). To the extent that a phenomenon (such as differential vaporization) is repeated in analyzing these effects, any such repetition should be considered to be supplemental rather than additive.

This report should not be considered to be a recommendation for or against the Webster-Heise valve or the related technology. There is not yet enough evidence to support such a judgment either way. The data that is available, however, suggests that a closer investigation of it by the auto industry and by the Federal Government would not be inappropriate. If its potential for greater fuel conservation, reduced emissions, and lower octane requirements can be even partially realized, the introduction of the Webster-Heise valve could be a very significant development.

II. EXECUTIVE SUMMARY

From the inception of the gasoline-powered spark-ignition engine, there have been numerous attempts to improve the condition of the charge reaching the cylinders. The carburetor allows the proper amount of gasoline and air into the engine but, because much of the fuel is in the form of liquid droplets (which will not burn in that form), combustion cannot occur at maximum efficiency. This causes undesirable effects such as "engine knock", imperfect fuel distribution to the cylinders, cycle-by-cycle variations, dieseling, engine deposits, less than optimum conversion of heat to work, increased engine wear, increased fuel consumption, loss of power, some driveability problems, and increased pollutant emissions.

The auto industry has attempted to solve the problem of inadequate vaporization by increasing the temperature in the intake manifold to heat the incoming air and fuel. This increases the rate of vaporization, but the high temperature in the manifold greatly reduces the density of the air that is admitted to the cylinders. This provides less air for combustion and expansion in the cylinders, resulting in reduced power. To deal with the problem of "knock", tetraethyl lead or other additives are used to slow down the rate of combustion. They allow the engine to operate but introduce additional losses of thermal efficiency. The slower burn also gives nitrogen oxides (NOx), a principal contributor to smog and acid rain, a greater opportunity to form. Tetraethyl lead has been associated with health effects, particularly on children, and is currently being phased out of gasoline as a result.

Both of these pollutants are currently the subjects of debate in the Congress.

The Webster-Heise valve was developed to deal specifically with the combustion problems caused by incomplete vaporization. It is not a carburetor but is a valve that fits below the carburetor and extends into the intake manifold. According to the Webster-Heise Corporation, it causes more of the gasoline in the air/fuel mixture to vaporize at any given manifold temperature and provides complete vaporization at intake manifold temperatures as low as 125 degrees F. This claimed achievement is made possible, according to the company, by a transverse shearing of droplets in the gasoline spray by highly turbulent air followed by passage through an area of lower pressure. These effects are produced by a matrix of thousands of small nozzles formed by two stainless steel concentric screens of different mesh size through which both gasoline droplets and air pass before reaching the intake manifold.

The turbulence and friction created by the passage of the air through the screens transfer enough energy to the gasoline to cause it to vaporize when it enters the lower pressure area of the intake manifold, according to Webster-Heise. It is further claimed that, because of early gasoline droplet vaporization, the vaporized gasoline has time to mix uniformly with air prior to entering the intake valve of each cylinder. This pre-vaporized and then thoroughly pre-mixed fuel charge permits equal distribution to, and within, each cylinder, thereby satisfying the conditions required for efficient combustion. At temperatures lower than 125 degrees F, even though the gasoline may not be fully vaporized, some efficiency gains are realized apparently due to the small droplet diameters resulting from the finer atomization and to improved mixing.

The effects of the Webster-Heise valve on combustion are very important, according to its designers. The vaporization of the gasoline prevents its collection as liquid on the metal surfaces of the cylinders and pistons. This also prevents dilution of the crankcase oil and promotes more complete combustion because the oxygen in the air has greater access to the hydrocarbon molecules and can oxidize them more completely. Carbon deposits are less likely to form as a result. Vaporization also reduces the occurrence of fuel-rich pockets in the extremities of the cylinders where detonation would otherwise take place. Catalysts such as lead, which slow down the reaction rate, do not appear to be needed because the conditions causing "knock" are not present to the same degree. This allows the combustion to occur more quickly, meaning that lower-octane fuels can be used without "knock", that more pressure can be exerted on the crank at the optimum moment, that NOx has less time to form, and that less heat can be transferred to the engine walls.

The Webster-Heise valve has been formally tested six times at EPA-recognized laboratories on all of the EPA vehicle tests on a wide range of octanes (97 to 75) and in the test laboratories of automobile and octane additive manufacturers. The test results vary to some extent with the type of test and the conditions under which they were run, but data (see Summary of Tests) comparing the Webster-Heise modified car with a baseline car (including the same car without the valve) show the following representative results:

1. Fuel economy increased from 6 to 20 percent;

2. Torque (power) at 1500 RPM increased from 13 to 40 percent;

3. NOx emissions declined from 4 to 48 percent;

4. Carbon monoxide (CO) emissions declined from 17 to 54 percent;

5. Hydrocarbon (HC) emissions declined from 5 to 13 percent;

6. Engine octane requirements declined by 10 to 15 points.

Tests to date indicate that the Webster-Heise valve enables an engine to operate on much lower octane than is possible in the unmodified engine. Because the charge is less likely to "knock" because of its conditioning by the valve, gasoline of lower octane (which burns faster than high octane) can be used effectively. In the Webster-Heise modification, gasoline with an octane rating of 75, blended and certified by the Phillips Petroleum Company, outperformed in all categories the 97-octane fuel used in the baseline car in comparative tests.

More work needs to be done to determine whether or not the test results obtained so far can be translated into commercial products with wide utility. However, the potential of a technological breakthrough of this magnitude provides a significant incentive for continued effort. If the valve were in use in all of the automobiles in the United States and if the fleet obtained the same results on average that the tests showed, the refining industry could save about 600,000 barrels per day (b/d) in crude oil by avoiding the extra processing now necessary to boost the octane of gasoline. It could also take much of the pressure off petrochemicals such as aromatics, which have other noncombustion uses. In addition to the 600,000 b/d that could be saved at the refineries, the gasoline conservation that could be realized by consumers through better fuel economy could be on the order of 650,000 to 1,300,000 b/d (somewhat more than the U.S. imports of crude oil from Saudi Arabia). The market for lower-octane gasolines would provide independent refiners with an opportunity to avoid the expensive investment in reforming equipment now needed to compete with the major oil companies in the manufacture of premium unleaded gasoline. It would also greatly reduce the pressure to increase allowable lead levels in gasoline and could accelerate the phaseout of tetraethyl lead as a gasoline additive (assuming appropriate timing). The positive health effects of eliminating lead could be supplemented by positive reductions in uncontrolled NOx, CO, and HC emissions and thus in control costs. The lower cost (about 20 cents per gallon less) of straight-run gasoline over premium unleaded could also benefit consumers.

Despite the fact that the production cost of the valve would probably be under $100 each and that it could be easily adapted to most new car engines, the institutional barriers to the acceptance of a new device can be formidable and preproduction testing may reveal unforeseen problems. In addition, the skepticism generated by the failures of others, plus the known costs and reliabilities of the technologies and products now in use, would have to be overshadowed by the performance and promise of a new technology and product. At this time, the auto companies, the most likely beneficiaries of the Webster-Heise technology, seem to be, for the most part, unsure of the next step. They have so far been skeptical. This may be due to the fact that it was not invented in their own research laboratories, and consequently they have no "in-house" experience with it. The relative advantages from the use of such a device could change if current trends toward fuel injection and dieselization continue, because the auto industry has invested large amounts of capital and effort in them. On the other hand, the U.S. auto industry has a desperate need to improve its existing products without substantial price increases, a need which might accelerate the rate of testing of the valve and possibly facilitate its subsequent acceptance. The disincentives of the cost and time required to evaluate the valve must be weighed by a company against the incentives of potentially improved performance and greater buyer acceptance of the cars on which it is used.

More testing of the valve is clearly needed on a wide variety of vehicles to establish a larger data base before its full potential can be precisely determined. This would presumably be the responsibility of private industry but some have proposed that the Federal Government might take an active role in evaluating it. The Government has testing facilities and vehicle fleets that are sometimes used for such purposes. Such testing, however, can be expensive for the Government as well and the desirability of doing it must be weighed against competing demands on Government resources. Because the effects of the valve touch upon several major issues of concern to the Congress (lead levels in gasoline, oil conservation, air quality, competitiveness of the auto industry, and others), this may be an appropriate course of action for consideration independent of the auto industry response.

III. INTRODUCTION

The history of the spark-ignition gasoline-powered engine is filled with attempts to improve it. Although there have been many modifications made in engine design over the past century, the fundamental process of delivering air and gasoline to the engine has not changed much over the years. Gasoline is still sprayed by the venturi jet of the carburetor through a needle valve into the intake manifold as air passes through it. This causes the gasoline to atomize into droplets which may be further reduced in size through secondary atomization when they strike the throttle plate (when it obstructs the flow at low engine speeds). This atomization increases the surface area of the droplets and increases the amount of vaporization that can occur. Because of the extremely short time available for vaporization to occur in the manifold, however, this is not generally sufficient to fully vaporize all of the gasoline. The presence of the liquid gasoline (rather than gasoline vapor) in the cylinders contributes to a variety of mixing, distribution, combustion, and lubrication problems. The carburetor, therefore, does an excellent job of metering out precise amounts of gasoline and air to maintain the proper air/fuel ratio but, except for breaking the liquid gasoline into small droplets which results in some vaporization, it does not completely overcome the phase problem. In order to increase the rate of vaporization, most auto manufacturers use high temperature (in the form of a hot spot on the bottom of the manifold or a heated water jacket around the manifold) to force more of the gasoline into a vaporized state. These elevated temperatures, however, reduced the density of the air reaching the cylinders, resulting in less power output from the engine.

Baffles are often used to promote mixing of the air and gasoline but these tend to restrict the flow and provide surfaces on which the gasoline can impinge and recondense.

Dozens of inventors, both individually and as employees of large corporations, have attempted to solve this phase problem but have been ultimately unsuccessful. These devices failed because of several common characteristics:

1. They were not variable but were optimized for only one steady-state condition (a fixed screen, for example). As a result, any change from the optimum engine speed would mean reduced performance which on the average was almost always worse than that for the unmodified engine.

2. They constituted restrictions because they reduced the space open to the passage of air and fuel, especially at high engine speeds, and consequently reduced the power the engine was able to produce.

3. Their gains were offset by losses (usually power or emissions) that made the devices impractical.

4. They attempted to modify carburetion in some way. Even though the carburetor is a very efficient metering device, it atomizes the gasoline but does not fully vaporize it.

5. They attempted to improve the vaporization rate of gasoline in an area <u>above</u> the throttle plate. As soon as the improved mixture, if any, impinged on the throttle plate it would reformulate droplets and destroy the gain.

6. They did not work (for some combination of the above reasons).

Some of these devices, such as the Pogue carburetor and its variations (which was marketed but turned out to be unsatisfactory because it was difficult to keep in proper adjustment), have been the subject of extreme claims. Because of the intense concern over fuel economy in the wake of serious international oil emergencies, the interest of the public, the auto industry, and the Federal Government has been raised and eventually dashed by these well-intentioned inventors who proved not to have the answer they sought. It should be noted that this applies to large corporations, including the auto companies, as well as to individuals. Some improvements in carburetion have been realized, but the fundamental phase problem still remains. Very little work, however, was done on charge conditioning below the carburetor.

As a result of this succession of technological disappointments, Americans have become highly skeptical of any new device that promises to improve combustion. This makes it more difficult than ever for a new idea to succeed. To do so, it must overcome the inertia of justified doubt generated over the last 50 years and especially over the last 10.

Sherwood F. Webster and Richard L. Heise claim to have discovered a means of vaporizing gasoline rapidly at low temperature. Their valve is a significantly different approach from the many devices which have preceded it. They have demonstrated in six formal tests and numerous informal ones that this has the effect of improving fuel economy, improving torque, reducing harmful exhaust emissions, improving driveability, and reducing the octane requirements of the engine on which it is used. Considerably more testing is needed, however.

Although some earlier devices employed a screen, it was a single screen that was fixed horizontally in the path of the air/fuel mixture. The Webster-Heise valve uses two screens, which have specific shapes, sizes, and proximity to each other that are critical to the process of early vaporization (see Physical Description). The valve conditions the gasoline and air so that each cylinder receives a charge that can burn more efficiently.

It is not unusual for major innovations to come from outside the auto industry. As Gushee et al. point out: 1/

> The tendency of innovations is to emerge from outside the industry. Several recent studies have shown this happening at a three to one ratio. The reason for this is that external industries do not have the commitment to the existing technology and do not have to worry about losing their existing market.
>
> Typically, an innovation is introduced on a a small scale, tested, and proved; gradually it penetrates the market. The period of experimentation varies widely depending on numerous factors, and involving the complexity of the innovation, the extent of the supporting system for the existing technology, and the social values affected. Several years is almost certainly the shortest period in which a major innovation can fill á market opportunity.
>
> In the auto industry, technological change seems to take a long time--at least it seems like a long time while one is in the period of change. Today's spark ignition engine produces about 10 times the horsepower per pound of engine that Henry Ford's best efforts could produce in 1900, but all seven decades have been needed for this progress to occur. In the area of technological substitution, these time lags are also apparent. It took 20 years for power brakes to be installed on half the new cars, 15 years for air conditioning on half the new cars, 10 years for power steering on half the new cars.

1/ David E. Gushee, Joseph P. Biniek, John E. Blodgett, and Mauree Ayton (Congressional Research Service). History and Future of Spark Ignition Engines. Committee Print prepared for the Senate Committee on Public Works, Serial 93-10, U.S. Govt. Printing Off.: Washington, D.C. September 1973. p. 3-21.

In a recent study on the competitive status of the U.S. auto industry, the National Research Council and the National Academy of Engineering concluded the following: 2/

> The clear competitive advantage accruing to products with advanced efficiency performance has created an incentive for the development of improved hardware. If the real price of oil continues to rise and we experience significant supply interruptions, the future course of product innovation may become more radical...
>
> We are concerned with the general pace of innovation as well as its general character. Two aspects are especially critical. The first is the diversity of technology growing out of the innovative process; the issue is essentially whether, for any given system, a new dominant design is apparent. The second aspect is the extent to which innovation departs from design concepts currently in use, whether innovation is epochal or incremental...
>
> The evidence suggests that innovation in the 1970s generally has proceeded first where the cost of change (in terms of its impact on the existing process) has been least. This serves to underscore the potential for change in future years. The technologies involve not only new design concepts but also in many cases totally new physical or mechanical and chemical principles. And indications are that such developments are not the flight of some engineer's fancy; extensive development work is under way in all areas and is some cases has been speeded up remarkably in the last two years...
>
> In terms of product technology, a period of intense technological competition may be just ahead.

2/ National Research Council and the National Academy of Engineering. The Competitive Status of the U.S. Auto Industry: A Study of the Influences of Technology in Determining International Industrial Competitive Advantage. National Academy Press: Washington, D.C. 1982. p. 132-157.

The Webster-Heise valve might be considered "incremental" in terms of its potential impact on the auto industry in that it probably would not require substantial changes in the existing equipment or production techniques. Its impact outside of the industry, however, could be considered "epochal" in terms of eliminating the need for gasoline additives, reducing crude oil imports, and improving air quality. In contrast, downsizing has been incremental in terms of technology but "epochal" in that it requires major changes in capital, labor components, management, and organization.

IV. PHYSICAL DESCRIPTION

The Webster-Heise valve is a relatively simple device, but it has a highly complex effect on the air and gasoline that pass through it and on the combustion that results. Of the 26 claims that were made in the two patent applications, all 26 were granted by the U.S. Patent Office. It is covered by two patents each in the United States and in nine foreign countries (Japan, West Germany, United Kingdom, France, Italy, Sweden, Canada, Mexico, and Brazil). 3/ 4/ A related patent covering turbine and oil-burner applications has also been issued, 5/ and one covering noncombustion applications such as spray drying, fluid-bed operation, and desalination is pending. 6/

The valve is mounted at the intake manifold opening below the carburetor and throttle plate and extends down into the intake manifold (Figs. 1 and 2). Air and gasoline are received from the carburetor and are directed through a slight funnel (the central down-tube) to promote centralized charge mixing. As needed, additional air can be drawn down the outer down-tube. At high speed or load conditions, air only

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3/ Sherwood F. Webster and Richard L. Heise. "Intake Manifold Variable Atomizing Valve." U.S. Patent No. 4,187,820. February 12, 1980.

4/ Sherwood F. Webster and Richard L. Heise. "Variable Capacity Fuel Delivery System for Engines." U.S. Patent No. 4,285,320. August 25, 1981, p. 1-8.

5/ Sherwood F. Webster and Richard L. Heise. "Fuel Delivery System for Combustion Devices." S.C./Serial No. 6,263,696. Allowed May 6, 1982.

6/ James F. Olmsted, Sherwood F. Webster, and Richard L. Heise. "Thermodynamic Conditioning of Air or any Other Gas to Increase the Operating Efficiency of Diverse Energy Consuming Systems." S.C./Serial No. 6,398,977. Filed July 16, 1982.

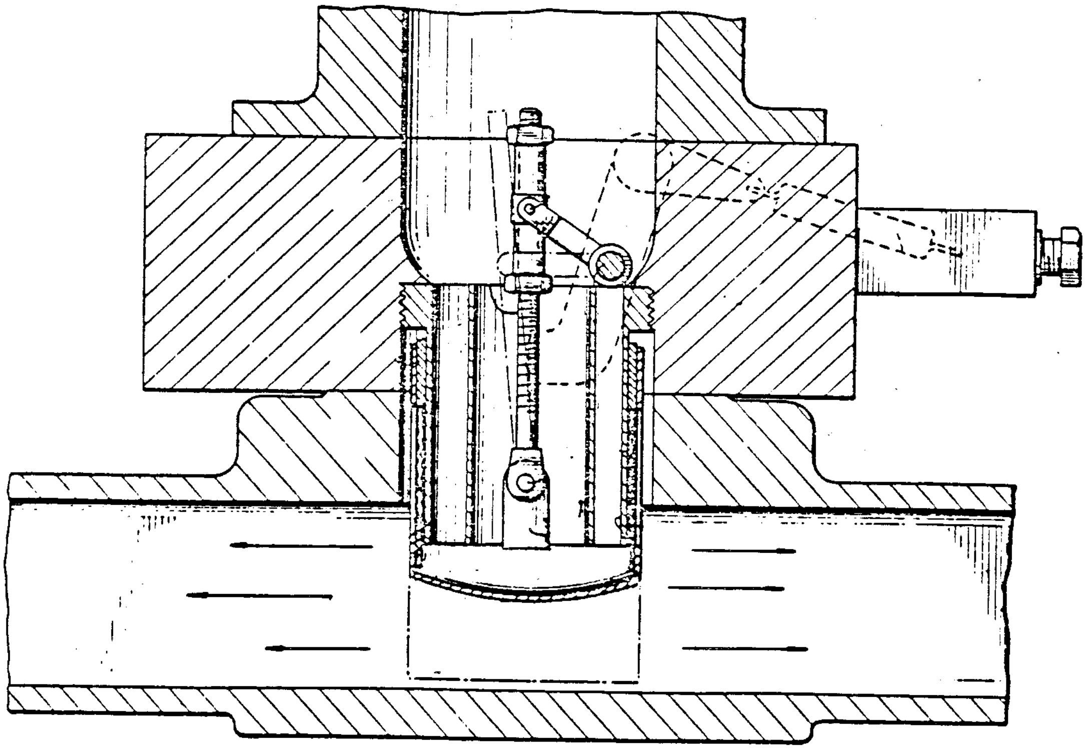

Figure 1. Vertical cross-section of the Webster-Heise valve indicating the range of movement and the direction of flow in the intake manifold.
Source: Webster-Heise Corporation

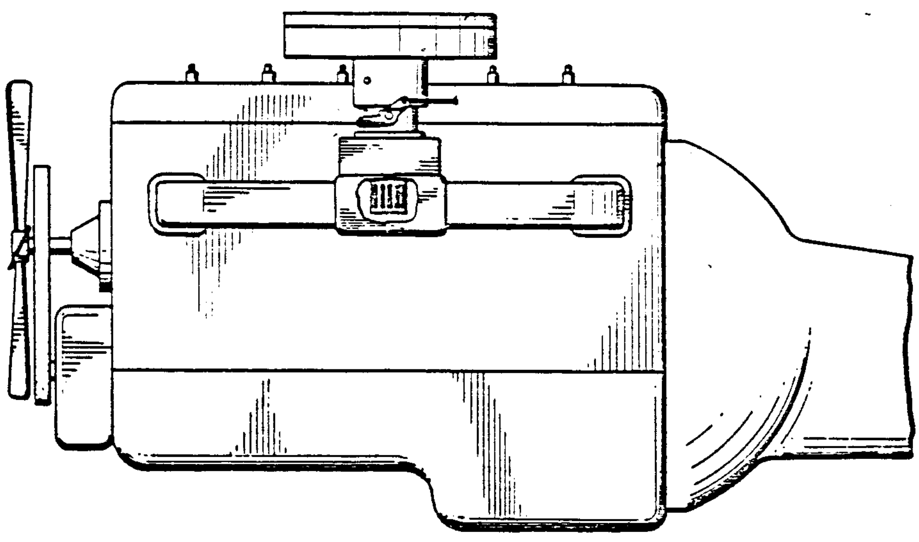

Figure 2. Cut-away view showing placement of the Webster-Heise valve in the intake manifold below the carburetor.
Source: Webster-Heise Corporation

is allowed into the outer down-tube (Fig. 3). At the bottom of the central down-tube, the gasoline/air mixture changes direction by 90 degrees and is directed toward the double-screen assembly that surrounds the valve (Fig. 4). The bottom of the valve is solid and slightly concave to aid in the redirection of the mixture. Because the flow from the central tube must cross the radial jump space between the central tube and the screens, it accelerates after changing direction and strikes the screens with force. The screens consist of a cylindrical #50 stainless steel mesh (coarse) immediately followed by a #120 stainless steel mesh (fine). The mesh sizes are critical and so is their proximity; they must be in contact to maintain the appropriate level of turbulence and to form the matrix of thousands of orifices that the gasoline and air must pass through. The air forces the gasoline through the orifices to produce droplets of extremely small diameters. Because of the lower pressure in the intake manifold, the high level of turbulence, and the higher energy level of the air, vaporization of the gasoline is believed to occur within a short distance after leaving the outer screen. Because moving air is the driving force and because turbulence is created by its passage through the valve, the gasoline vapor and air are thoroughly mixed. The radial structure of the screen assembly directs the gasoline/air mixture evenly toward the cylinders so that all receive the same quantity and quality of charge.

The valve is automatically regulated by engine demand. A one-inch vacuum differential between the interior and exterior of the valve is maintained by a vacuum regulator which senses the pressure at a point above the valve (but below the carburetor throttle plate)

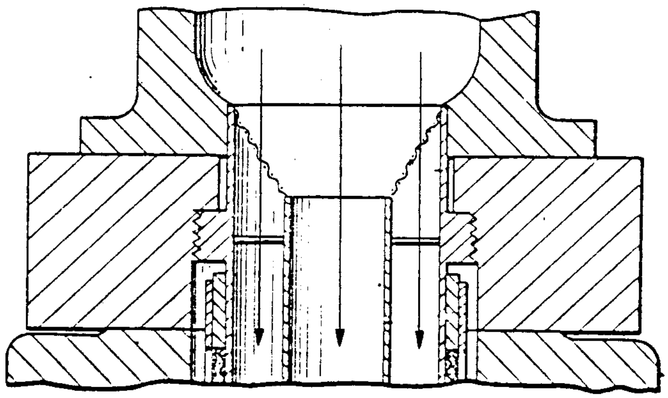

Figure 3. Vertical cross-section showing the central and outer down-tubes (note direction of flow).
Source: Webster-Heise Corporation

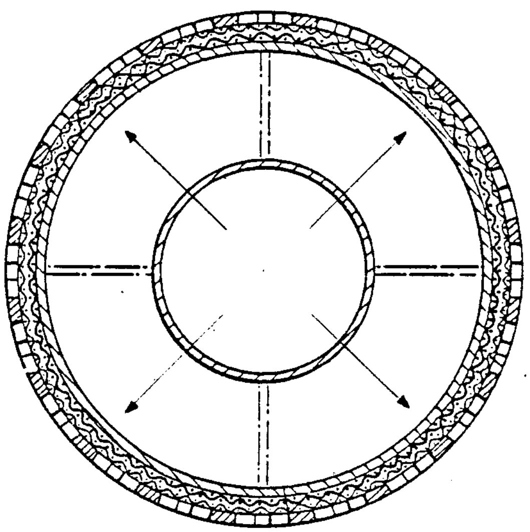

Figure 4. Cross-section (horizontal) indicating the position of the central and outer down-tubes relative to the double-screen assembly and the radial jump-space (note direction of flow).
Source: Webster-Heise Corporation

and at a point below the valve in the intake manifold. As the accelerator is depressed and more gasoline and air are required, the manifold vacuum is lowered. The vacuum regulator senses this pressure change and relaxes enough to permit the valve to descend further into the manifold under the greater force of the increased flow of gasoline and air. This exposes more of the double screen to accommodate and to process the greater flow. Because of this variability, there is no restriction to the flow except for a one-inch pressure drop (maintained by a vacuum differential valve) which enhances the vaporization effect and which constitutes a restriction only at wide-open throttle. As the velocity of the flow diminishes with lower engine demand, the vacuum regulator causes the double-screen assembly to retract to maintain the one-inch differential under all speed and load conditions.

The "double down-tube" is especially important to the performance of the valve. All of the gasoline droplets and most of the air from the carburetor are directed toward the center of the top of the valve where they are collected in a shallow funnel which accelerates them (through a Bernoulli Effect) through the center tube. As it exits the bottom of the tube, the gasoline/air mixture is forced outward in a radial pattern toward the double-screen assembly that surrounds the flow. Before the mixture reaches the screens, it must traverse a "radial jump space" across the width of the larger, outer tube. This causes the mixture to not only change direction by 90 degrees but also to accelerate toward the double screens. At the same time, air and a very small amount of gasoline vapor descend under atmospheric pressure through the outer down-tube. In addition to providing the radial jump space that the primary flow must cross, this secondary flow around the center tube adds more turbulence when it intercepts the primary flow and greater volumes of air when needed under high-speed or high-load conditions.

V. HISTORY

Development of the Webster-Heise valve began in 1978 when Sherwood F. Webster and Richard L. Heise decided to combine their knowledge and experience in an attempt to reduce the fuel consumption and pollution levels of modern internal combustion engines. 7/ Webster had worked in this field since 1959, mainly with variable venturi carburetors and cold manifolds, and Heise was well known in the Phoenix area as a master mechanic. At the outset, they decided that their approach would be to atomize all of the fuel below the throttle plate rather than to attempt separation of the gasoline into its "light" and "heavy" components. They concluded that a cylindrical valve that could move up and down in the intake manifold in response to engine demand would be the best way to eliminate the problems that were known to exist with fixed systems.

The problem confronting them at that point was the need to find a simple yet satisfactory atomizing mechanism to reduce the diameters of the gasoline droplets. Even though both inventors were familiar with the failure of single horizontal screens in the past, they decided to experiment with a variety of screens, not knowing whether any would work in their application or not. A test apparatus was constructed consisting of a simple venturi extending above the container of water in which it was immersed and an air compressor which directed a continuous flow of fast-moving air over the venturi to simulate the flow of the charge through an automotive carburetor.

7/ Richard L. Heise and Sherwood F. Webster. Personal communication to David Lindahl, August 9, 1982.

Various screen sizes from #50 to #350 were tried with no success. The water would merely run in large drops down the side of the screen onto which the flow was directed. After two months of screen testing, it was apparent to both Webster and Heise that a single screen would not work, as earlier inventors had already shown. In the process of changing from one screen size (#50) to another (#120), however, Heise accidentally held both screens together and noticed to his astonishment and that of the others present that a totally unexpected phenomenon was occurring. The water was no longer falling in large drops on the impact side of the double-screen combination, but the entire flow was passing through the screens in a virtually invisible mist. Only when a watch crystal was placed in the flow downstream from the screens did small droplets reform and become visible.

On the basis of that discovery, they added a double screen assembly to the valve and assumed that they had achieved a major breakthrough in automotive fuel conditioning. They assembled an early prototype of the valve and eagerly installed it on a 1972 Chevrolet pickup truck. They were disappointed to discover that not only was there no apparent gain, they actually lost fuel economy. This setback was followed by a period of trial and error during which numerous modifications were tried and rejected as ineffective. After a succession of these failures, they concluded that the problem was due to the fact that the flow from the carburetor was not striking the screens with sufficient force because of the low angle of approach. To correct this situation, they developed the double down-tubes, which provided space between the bottom of the central tube and the double screens to force the flow to strike the screens directly at right angles rather than at acute ones. After further experimentation, they observed that the maximum effect appeared to occur when the pressure differential between the interior and the exterior of the valve was held to a constant one inch. A vacuum valve was used to replace the spring which originally controlled the action of the valve so that more precision could be obtained. As a result of these incremental improvements to the basic valve over a six-month period, the fuel economy of the truck was raised by about 0.5 MPG at a time from 12.5 MPG to 16.0 MPG with noticeably better performance, according to Webster and Heise.

As the gains became more apparent so did the need for more sophisticated testing. Webster and Heise formed a corporation to attract the capital necessary to complete the development of the valve. Approximately $450,000 was raised privately, including $75,000 from Webster. This was used to cover the cost of patents, tests, vehicles and equipment (including a complete dynamometer), professional services, legal fees, and travel. 8/ Both Webster and Heise have worked exclusively on the development of the valve since 1978.

In early 1980, after the initial development work was completed, the inventors asked the Ethyl Corporation to test the device. Webster and Heise suspected, but had not yet confirmed, that use of the valve reduced engine octane requirements. Their presumption was that Ethyl would be interested in an alternative to chemical octane because of the lead phasedown in gasoline that was underway as a result of the Clean

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8/ Sherwood F. Webster. Personal communication to David Lindahl. August 10, 1982.

Air Act. Ethyl agreed to test it at its research laboratory near Detroit (see Test 1, Summary of Tests). During the test at Ethyl, an octane requirement reduction of 10 points was established, an improvement in distribution was verified, and no loss of power was measured (See Test 1, Summary of Tests). 9/ Ethyl wanted to dismantle the engine and the valve to analyze it further over a one-month period, which was acceptable to Webster-Heise, but would not agree to cover Webster-Heise's expenses during the testing period. As a result, Webster and Heise decided to use their limited funds for testing at other certified laboratories.

In August, 1980, tests were conducted at the Environmental Testing Corporation (ETC) near Denver, Colorado (an EPA-recognized test facility). These tests, as shown in the summary of tests, confirmed earlier, less complete tests that had shown gains in fuel economy, reduced emissions, and lower octane requirements. On the basis of those tests, invitations were sent to all of the major automobile and oil companies to attend the formal introduction and demonstration of the valve at ETC on October 15, 1980. Fifteen major corporations sent representatives who witnessed the operation of the test car and a baseline car (see Test 4, Summary of Tests). EPA tests were run on both cars, and three different fuels were used (97-indolene, 85 pump-grade unleaded, and 75-octane specially blended and certified by Phillips Petroleum Co.). The gains demonstrated in these test were consistent with the earlier tests. At the demonstration, John O. Marsh, Jr., the Webster-Heise corporation counsel (now Secretary of the Army), offered to license the valve to any U.S.

9/ William Adams (Chief Engineer, Ethyl Research Laboratory). Personal communication with David Lindahl. July 13, 1982.

corporation and to provide a five-year moratorium on its use in foreign cars imported to the United States.

Following the demonstration, the Standard Oil Company of Ohio (Sohio) expressed interest in the Webster-Heise valve. In arranging for further testing, Sohio noted that: 10/

> ...The data from these previous tests do indicate the potential for reduction in octane, improved fuel economy, reduced emissions, and possibly improved drivability. Together these benefits, if realized, could represent significant value. Therefore, we are now exploring ways to further evaluate the valve.

Sohio urged the Ford Motor Company to test the valve as part of a joint project. Ford agreed to a three-week test, to be followed if successful by an eleven-month testing program with the Webster-Heise Corporation. Ford required that Sohio not participate in the test and that no disclosures of data be made while the tests were being conducted.

The tests were conducted at the Ford laboratory in Dearborn in late January, 1981. The baseline tests were conducted prior to the arrival of Webster and Heise. In the first test with the valve (Figs. 16 and 17), significant gains were shown in torque and fuel economy (see Test 5, Summary of Tests). Ford was concerned, however, that some of these gains might be due to the fact that the baseline engine (without the valve)

10/ Richard D. Smith (Manager of Corporate Development, Standard Oil Company of Ohio). Personal communication to E.T. Taber, October 31, 1980. (The personal communications in footnotes 9-13 are in the public record as part of Civil Actions 81-2867 and 81-2868, U.S. District Court, District of Columbia).

had been contaminated by carbon deposits during the baseline tests. 11/ The second test (Fig. 18) was a very demanding wide-open throttle test. The gains of the valve in this test were also apparent but above 3000 RPM they dropped to the level of the baseline production system with heat due to the limited size of the prototype valve. Webster offered to enlarge the valve to accommodate these testing conditions but was told that no modification was necessary. 12/ Ford then exercised its option under the testing agreement to terminate the tests. Ford informed Webster that "it is Ford's opinion that the Webster-Heise device is not the most appropriate means of eliminating the necessity for carburetor heat" and that "the Webster-Heise device is not of interest to Ford at this time." 13/

The spark-advance test conducted at the Ethyl Corporation is a relatively severe engine test, although not as severe as the torque test performed at Ford and ETC, and it simulates the rapid acceleration sometimes encountered in normal driving. The valve apparently worked well in these tests, providing more fuel economy on low-octane gasoline than did the baseline engine. The early prototype valve completed the spark-advance test and did the same amount of work with approximately four inches more vacuum. This does not mean, however, that there was a restriction due to the presence of the valve (beyond the one-inch differen-

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11/ Robert D. Sanborn (Associate Counsel, Ford Motor Co.). Personal communication to S.F. Webster. June 12, 1981. p. 2.

12/ Sherwood Webster. Personal communication to Donald E. Petersen. February 6, 1981. p. 4.

13/ Sanborn, p. 2-3.

tial built into it). It does mean that the same work could be done on less fuel or more work could be done at the same vacuum, although the effect diminishes as engine speeds increase. In the spark advance tests at Ethyl, despite the octane and fuel economy gains, no loss of power was measured. In the Ford wide-open throttle test, the valve size limitation of the early prototype was encountered above 3000 RPM on 75 octane (R+M/2) gasoline. In order to accommodate these extreme conditions, a second-generation prototype was made 30 percent larger, so that it could descend further into the intake manifold under full throttle and expose more screen area to prevent any unwanted pressure drop. The vacuum differential at full throttle is about one inch due to the presence of the valve (not to be confused with the vacuum created by the throttle plate at lower RPMs) (see Test 6, Summary of Tests). Despite the presence of manifold heat in Test 6, both the torque and fuel economy gains were substantial.

In order to fully evaluate the new, larger prototype, Webster and Heise decided to test it on a new state-of-the-art automobile with electronic carburetion (which maintains a relatively constant air/fuel ratio) and the latest pollution controls. A 1982 Oldsmobile Cutlass Supreme was purchased and a complete baseline test prior to conversion was made at the Environmental Testing Corporation. The jacketed design of the Oldsmobile intake manifold, they discovered, was not amenable to heat removal. They also found that the design of the exhaust gas recirculation (EGR) equipment did not allow for adjustment (less was needed to control NOx with the Webster-Heise valve) without altering other calibrations in the closed-loop system. Without the volumetric efficiency gains from a cooler manifold and with the higher EGR, they were concerned that their gains might be reduced, particularly torque and NOx. The test (Test 6, Summary of Tests), however, showed significant gains over baseline, even with 75-octane fuel instead of 97-octane. NOx decreased 45 percent despite a larger spark advance, and other emissions also declined. Fuel economy increased from 31.4 MPG to 35.6 MPG, well above the EPA highway standard. Torque was also significantly increased. To confirm these results, the test was run again with the same (and in some cases even better) results. The emissions were even rechecked on another computer to verify the readings. Webster-Heise concluded from this test that in an optimized engine (with a cooler manifold and less EGR) even greater gains might be achieved. 14/

14/ Sherwood F. Webster. Personal communication to David Lindahl. August 10, 1982.

VI. STATUS AND OUTLOOK

The Webster-Heise Corporation makes several claims for its valve and offers data from several tests (see Summary of Tests) in support of its claims. It is claimed by Webster-Heise that the valve does the following:

1. Reduces engine octane requirements by 10 or more points;
2. Reduces gasoline consumption by as much as 40 percent;
3. Reduces the formation of nitric oxides (NOx) by as much as 45 percent;
4. Reduces the formation of carbon monoxide (CO) by as much as 20 percent;
5. Reduces the formation of unburned hydrocarbons (HC) by as much as 10 percent;
6. Increases torque as much as 20 percent;
7. Eliminates stalling and flooding, especially on cold starts;
8. Reduces the formation of deposits that cause engine wear and contamination of lubricants;
9. Requires no maintenance.

Some automotive engineers, among others, are skeptical. Their concerns include the following:

1. The pressure drop resulting from the presence of the screen could result in a power drop.
2. The reduction in manifold heating could be a problem in sub-zero operation and could cause an increase in HC emissions.
3. It might "gunk up" over time and be rendered inoperable.

4. There are more appropriate methods in development to achieve the same gains.

These points, both pro and con, are addressed individually in more detail in the sections on precombustion, combustion, and post-combustion effects. Overall, there is not enough evidence, based on the number of tests, to be considered conclusive.

General Motors and Chrysler have reportedly expressed interest in the valve but have conducted no formal tests. R.M. Hokanson, the Chrysler representative at the ETC test on October 15, 1980, made a positive recommendation to his company: 15/

> I think this device has merit for our company and recommended that we investigate the possibility of testing this device on our products as soon as possible.

Despite recommendations such as these, no further testing has been done by any of the auto or oil companies. Most of the major oil companies have already made substantial investments in facilities to make premium unleaded gasoline. This product is more profitable (while it is in short supply) than the other grades of gasoline and cannot be readily made by many independent refiners. The market for high-octane unleaded gasoline is growing faster than any other grade because the octane requirement of cars increases as engine deposits accumulate. If all cars could use the same low-octane gasoline, it could make obsolete many of the existing facilities built at great cost by the majors. It could also eliminate the need for expensive octane additives and could improve the competitive position of the independents with respect to

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15/ R.M. Hokanson (Chrysler Corp.). "Demonstration of Intake Manifold Variable Atomizing Valve." October 20, 1980. p. 2.

the major oil companies. Use of the valve, however, could also save the majors large investments in additional reforming facilities that might far outweigh these competitive aspects.

One problem that Webster-Heise could expect to encounter on the long path to acceptance would be that of competing technologies. All of the major automotive companies have invested large amounts of effort and capital in devices that may not be compatible with the Webster-Heise valve. Fuel-injection has become increasingly popular as a means of restoring some performance and diesels have found favor as a means of improving fuel economy. Some companies have committed considerable resources to these approaches and may prefer to continue them rather than to adopt a new device. Others may conclude that in the medium term (3 to 8 years) other approaches might be more competitive. In addition, most auto companies have research projects of long standing that they may feel a need to protect from a competing device. It may be that the Webster-Heise valve will be found to improve the "in-house" projects as well. It has been suggested, for example, that the valve could be useful on a spark-assisted diesel. If so, companies that have shown a strong interest in dieselization may find this development to be complementary rather than contradictory. In any event, the reaction of the auto companies to this device could be expected to vary considerably depending upon their own individual interests and priorities.

Another barrier of considerable significance is the "not-invented-here" syndrome. There is a strong preference in the auto industry to use ideas developed "in house." Innovation from outside the industry must compete with these projects in which an investment has already been made. "In-house" projects that address the same problem will generally be given preference, if for no better reason than that the companies are already familiar with them and have data bases for them. It is also possible that having been shown that a type of improvement is possible, they may seek some other means of achieving similar gains without employing a particular technology purchased from outside.

Because of the high cost of automotive testing, the valve has been tested on a limited number of test vehicles under a limited range of circumstances. As a result the data base is not as large as most would like. The more data that becomes available, the stronger are the conclusions that can be drawn. Enough data has been obtained to demonstrate the promise of the valve, but not enough has been collected to erase all doubt among those who might risk large sums and professional reputations in developing and introducing the valve in mass-produced vehicles. It would clearly benefit from further testing, especially in actual road operation.

The cost of obtaining the rights to manufacture the Webster-Heise valve for use on new automobile engines may or may not inhibit its acceptance. The Webster-Heise Corporation has expressed willingness to accept "standard and customary" royalty procedures followed in the domestic auto industry. That would consist of five percent of the manufacturer's invoice cost for the first million valves, four percent for the second million, three percent for the third million, and two percent for all subsequent production. 16/

16/ Sherwood F. Webster. Personal communication to David Lindahl. August 31, 1982.

The response of the auto companies to date has been noncommital. Only one company, Ford, has formally decided not to use the valve. Others may or may not; they have apparently not decided. Whether or not it will be accepted at all by the domestic auto industry is currently uncertain. If that proves to be the case, then foreign auto companies (who have reportedly expressed interest in the valve) may choose to pursue the necessary additional testing and development.

VII. POTENTIAL BENEFITS

The tests which have been conducted so far indicate that the Webster-Heise valve could have a significant beneficial impact on several major issues. The potential benefits described in this section are based on the assumptions that the demonstrated gains, which so far are suggestive but not conclusive, will be further substantiated in additional tests and that the use of the valve would be widespread. If that proves to be the case, then a substantial reduction in crude oil requirements may be possible at the refinery level. In addition, greater fuel economy in valve-equipped engines might lower the need for crude oil even more. To the extent that the valve can reduce the emission of pollutants and the need for toxic or carcinogenic additives to gasoline, air quality could be improved. If the valve proves to be a major advance in increasing the fuel economy and performance of modern internal combustion engines, it could be a major technological breakthrough that could attract new interest to domestic automobiles and increase the competitiveness of the U.S. auto industry.

A. Refinery Feedstock Conservation

One of the problems facing refineries is the need to increase octane and to make increasing amounts of unleaded gasoline, especially premium unleaded, as the use of lead is phased out. The manufacture of unleaded gasoline has proven to be a costly process in terms of the extra crude oil consumed in making it and of the reconfiguration necessary to increase its octane above the 82 or 83 level that it has when it comes straight from the fractionating tower. The extra processing used to make unleaded fuels consumes about 9.2 percent more crude oil than does straight-run gasoline, according to the Ethyl Corporation. 17/ The hydrocarbons used to increase the octane levels have many other uses in the petrochemical industry and their allocations have been a source of concern during oil supply emergencies.

The high cost of making premium unleaded gasoline, for which demand is increasing faster than for any other gasoline type, has placed the independent refiners at a competitive disadvantage to the major oil companies. Because the refining industry has been depressed and profits have been limited or nonexistent in recent years, most investors have been reluctant to lend the capital needed to build the octane improvement facilities necessary to compete with the majors for a significant share of the premium unleaded market. The majors have had considerably more financial flexibility in upgrading their production facilities during this period. As a result only the majors, to a large extent, are able to make the high-octane unleaded gasolines that will perform satisfactorily in new cars after engine deposits accumulate and their octane requirements increase. In the United States, there are 115 refineries (nearly 40 percent of the total) that lack the catalytic reformers needed to make unleaded gasoline, and all of these have capacities of 48,000 b/d or less. 18/ This is a major reason for the independent refiners' desire to have

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17/ George H. Unzelman (Ethyl Corp.). "Return to Leaded Seen Saving 3 billion bbl of U.S. Crude." Oil and Gas Journal. Oct. 15, 1979. p. 106.

18/ Oil and Gas Journal. "U.S. Lead Entitlements Urged." May 31, 1982. p. 177.

allowable lead levels in gasoline increased despite strong environmental opposition to that proposal. Lead is preferred by refiners because it is the least costly octane enhancer currently available. The Lundberg Letter recently observed that "the emergence of premium unleaded allows regular unleaded to drop in octane, and refinery profitability to be enhanced." 19/

If the entire fleet of automobiles in the United States could use gasoline 10 octane points lower than that currently sold with no off-setting losses in fuel economy, performance, or emissions, it would greatly reduce the crude oil requirement of the refining industry, eliminate the need for large capital investments in facilities, improve the competitive position of small refiners, and reduce the cost of making acceptable fuels for new cars.

In its analysis of the potential impact of the Webster-Heise valve on refining, the PACE Company, well known for its consulting and engineering work for the refining industry, reached the following conclusion: 20/

> When we evaluated the impact of a ten-octane (R+M/2) reduction in our 1990 base case, over 600,000 barrels per day less crude oil were required to meet the product slate. This reduction is due to fuel savings in the refinery on the assumption that fuel quality was reduced and less processing was needed. If further efficiency can be gained through fuel/engine optimization, savings would be greater.

19/ Lundberg Letter. "As the Market Clears Artifical Price Spreads Collapse." Vol. IX, No. 32. June 11, 1982. p. 6.

20/ John Matson (The Pace Company Consultants and Engineers). Personal Communication to S.F. Webster. April 10, 1981. p. 1.

PACE also noted that the production of lower-octane gasoline could use components, such as naphtha, which have clear octanes of 40 to 65 and which are normally surplus for many refiners.

The objective, according to PACE, should be: 21/

> ...To simultaneously minimize fuel consumed in the engine and the refinery. Most of the refinery fuel saved in our analysis occurs in about the first five octane number reduction, thus the optimum engine to take advantage of octanes in this range would result in maximum miles per barrel of crude.

PACE also identified seven areas of refining that would be helped by the production of low-octane gasoline that could be used in engines equipped with the Webster-Heise valve. 22/

1. Reforming feed rates and severities would be reduced;
2. Processing severity would be decreased and per-barrel utilization of crude oil would be increased;
3. The need for hydrocracking would be decreased;
4. The need for alternate blendstocks would be decreased;
5. The availability for aromatics would be increased;
6. The need for liquefied petroleum gases (LPG's) would be reduced; and
7. The need for octane additives would be eliminated.

B. End-Use Fuel Conservation

As indicated in the section on fuel economy, the improvements in fuel economy with the Webster-Heise valve vary with the type of

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21/ Matson, p. 2.

22/ The PACE Company Consultants and Engineers. Fourth Annual PACE Energy and Petrochemical Seminar; Houston, Texas. November 1980. p. D-8.

driving and other factors. The range of improvement is about 10 to 20 percent, with 15 percent possibly representative of the average improvement that could be expected in normal driving. If the valve were in use in all of the cars in the United States and if the best-case improvement of 20 percent were realized, the daily savings in gasoline consumption could be approximately 1.3 million b/d. At the worst case improvement of 10 percent, the demand for gasoline could be reduced by 650,000 b/d. This, combined with the fuel conservation at the refineries, could yield total savings of more than 1.25 million b/d (37 percent of total crude oil imports in the second quarter of 1982 and 79 percent of the crude oil imports from OPEC during that period). 23/

Because several years would probably be required for all of the vehicles in the fleet to be equipped with the valve, the reduction in gasoline consumption would be gradual as the number of cars using it increase. Nearly a decade would probably be required for most of the fuel economy improvement to be realized. This could be accelerated, however, if the market acceptance of new valve-equipped cars were to exceed the normal rate of replacement. The primary point of introduction would most likely be in new cars, but retrofitting old ones is also a possiblity. If the engine deposits were removed, most older cars could probably use the valve. Cars five years old or newer might require a change in EPA regulations preventing changes to an engine once it is certified.

23/ Petroleum Intelligence Weekly. "Plunge in U.S. Imports Radically Alters Crude Supply Mix." Vol. XXI, No. 35. August 30, 1982. p. 1-2.

C. Air Quality

The emission improvements indicated with the valve could become a major factor in the debate over air quality in general and gasoline lead levels in particular. Lead and other additives such as aromatics (benzene and others) are either toxic or carcinogenic and pose a public health threat. 24/ Reducing automotive pollution is of major importance in achieving better air quality because it is responsible for approximately 50 percent collectively of all the hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) that are emitted each year. 25/ A substantial reduction in these automotive emissions could greatly improve air quality, particularly in urban areas where concentrations of pollutants are especially high.

The automobile industry has made considerable progress in pollution control, but the results have been achieved at a high cost to the consumer. Performance has been sacrificed in many models in order to achieve lower emissions and higher fuel economy in new cars. The control devices themselves (such as dual-bed converters) can become clogged or contaminated and can cease to function properly. When they malfunction, the pollution levels can rise to extremely high levels and in some rare cases can prevent restarting once the engine is stopped. Because the controls can be troublesome and sometimes do not work well enough even to get through the EPA certification process,

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24/ McGinty, Lawrence. "A Clean Case Against Lead in Petrol." New Scientists. May 27, 1982. p. 570.

25/ F.V. Bracco (Princeton Univ.). "Combustion and Chemical Kinetics Problems in Internal Combustion Engines." In Progress in Astronautics and Aeronautics, Vol. 62. American Institute of Aeronautics: Princeton, New Jersey. 1977. p. 162.

the automakers must occassionally ask for emission waivers. In addition, these controls are relatively complex and add up to $600 to the cost of new cars. 26/

Much of the controversy is currently focused on lead because the independent refiners have asked that the lead levels allowed in gasoline be raised. This request, if granted, would permit them to increase the octane ratings of their gasolines so that they could compete at lower cost with the major oil companies. The majors, however, contend that the exemptions gave the small refiners (and blenders who are not mentioned at all in the regulations) a competitive advantage and, as a result, the special exemption should be removed entirely. 27/ The independent refiners, however, claim that they cannot afford the average investment of $10 to 20 million each for the reformers necessary to chemically raise the octanes of their unleaded gasolines. 28/

Extensive testimony was received by Congress on the subject, most of it strongly against weakening of the lead standards. Very little support was offered for eliminating the standards completely. A cost-benefit analysis prepared by EPA did not support an easing of the lead levels, estimating that elimination of the standard would save

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26/ Joseph P. Biniek and David M. Lindahl. "Environmental Issues Associated with the Auto Industry." Congressional Research Service. November 2, 1981. p. 13.

27/ Sandra Sugawara. "EPA Trying to Ease Out of a Leaden Box." Washington Post. May 21, 1982. p. A19.

28/ Felicity Barringer. "Debate Over Lead in Gasoline Revs Up Agains." Washington Post. Oct. 15, 1981. p. A 11.

the refining industry $100 million per year but would cost between $140 million and $1.4 billion per year to treat an additional 200,000 to 500,000 children for the lead poisoning that would be caused by the higher lead levels. 29/ An Environmental Protection Agency official recently said in a memorandum that lead air pollution monitors had repeatedly underestimated the lead content of air because they were located "at sites which were not designed to measure maximum lead concentrations. 30/

NOx is best known as the principal cause of smog, but it is also an important factor in "acid rain." The importance of NOx in the debate over acid rain was summarized in a report for the Canadian Embassy: 31/

> NOx currently is responsible for approximately one-fourth to one-third of the acid rain--but this proportion is expected to increase over the next two decades. In parts of the West, NOx is already the major contributor to acid rain. If current trends continue, by 1990 NOx-caused acid rain could equal or exceed the acid rain caused today by SO2.

29/ Joel Schwartz (Environmental Protection Agency). "Health Effects of Gasoline Lead Emissions." Cover Memorandum to accompany the Department of Housing and Urban Development official comments on the lead phasedown proposal. May 11, 1982. p. 7 and 12.

30/ Robert Kennedy (Chief of State and Local Controls Program Section, Environmental Protection Agency). Internal Memorandum, January 27, 1982. p. 1.

31/ Wellford, Wegman, Krulwich, Gold, and Hoss (prepared for the Canadian Embassy. "Fact Sheet on Acid Rain." 1982. p. 3-7.

> NOx pollution also is associated with the production of ozone. High levels of ozone cause crop damage, forest damage and a number of respiratory problems. Ozone, like acid rain, is a product of atmospheric chemistry acting on pollutants. It, too, is principally a transboundary pollutant; most of its damage is done outside the state or province where the NOx originates.
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> NOx from metropolitan centers along the Pacific Coast is being deposited hundreds of miles to the east in the Sierras and Rockies in the form of nitric acid-contaminated rain or snow. Studies published in Science magazine show that precipitation with 4.6 pH (at least five times normal acidity) is occurring frequently in parts of Colorado. Mountain lakes in Colorado and California are becoming acidic, with local residents concerned about potentially adverse consequences for the tourism and recreation industries.

Most of the emission standards promulgated under the Clean Air Act of 1970 are under pressure for revision. Under the Act, the 1971 NOx levels were supposed to be reduced by 1976, but subsequent administrative and legislative actions have delayed the deadlines for NOx, CO (a poisonous gas), and HC (which can be carcinogenic). The current NOx standard of 1 gram per mile would probably provide for a steady reduction in NOx over the next decade but, if the auto industry request for a relaxation of the standard to 2 grams per mile were granted, there would probably be no decrease but a slight increase instead. 32/ The industry, on the other hand, claims that these reductions would allow them to save billions of dollars in

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32/ Wellford, et. al.

"unnecessary controls" which could be used to increase the competitiveness of their products and which might not have a substantial effect on the environment and human health. The standard for HC is 0.41 gram per mile, and for CO it is 3.4 grams per mile.

Data from initial tests of the Webster-Heise valve suggest that its widespread use could make possible a solution to this economic/environmental impasse. Because of the substantial reduction of NOx and CO (and HC to a lesser extent), the stricter standards could be met with existing equipment. It is very possible that some pollution controls could even be removed outright or replaced with less expensive ones. The dual-bed converter and closed-loop feedback systems, for example, probably could be removed in favor of simpler pre-1981 systems. 33/ A smaller, less-expensive converter might be possible, and some controls such as knock sensors probably could be eliminated. Even though some catalytic conversion and exhaust gas recirculation would still be required, it may be possible to reduce the cost of necessary emission controls by about $300 per car. 34/ This could more than offset the cost of the Webster-Heise valve, which almost certainly would cost less than $100 each.

D. Competitiveness of the U.S. Auto Industry

The U.S. auto industry is in trouble. Since the turn of the century, it has had a vital place in the economy; its success and its

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33/ Biniek and Lindahl, p. 18.

34/ Sherwood F. Webster. Personal communication with David Lindahl. August 10, 1982.

productive genius have long been a source of national pride. For a number of reasons, including increased concerns over fuel economy and air quality and the pressure from low-cost high-quality imports, the domestic industry has serious problems to overcome.

The importance of the industry to the economy is well known. Employment in 1978 was 14 million people, about one-fifth of all the jobs in the Nation. 35/ Indirectly, many more people in other industries rely on sales to the auto industry and on purchases by its workers. It is not surprising, therefore, that the current depression in that industry has been a great setback for the economy in general. In 1980, auto production was the lowest it had been in 20 years, while auto imports (mainly from Japan and Germany) were at record highs. In that year, the industry lost $4.2 billion, the largest loss in its history, and severe losses have been experienced in 1981 and 1982.

Compounding the problem for the auto industry is its need to meet this competition by investing in new models at a time when it can least afford to do so. The severe monetary losses have not only cut into income but also into company reserves. Faced with dwindling reserves, limited cash flows, and record-high interest rates in a highly competitive market, the industry is clearly in a dilemma.
The industry has repeatedly recognized the need for innovation in its struggle for economic viability in the face of strong competition from foreign manufacturers. As the National Research Council and the National

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35/ Biniek and Lindahl, p. 3.

Academy of Engineering point out in their report on the competitive status of the U.S. auto industry: 36/

> The transformation of the auto industry from a mature, technologically quiet industry into a hotbed of innovation and change creates opportunities for U.S. firms to attain competitive advantages through development of radically new products. The same, however, can be said of the Japanese and the Europeans. Whether U.S.-based production regains lost market share by creating and exploiting new markets depends on its ability to "out innovate" its competitors.

The least costly path to recovery would be for the auto companies to make the most efficient use of existing equipment and tooling while buying time to develop more advanced lines. The Webster-Heise valve, if proven successful and if accepted by the industry, could easily be adapted to most new cars at little or no additional cost because unnecessary equipment probably could then be removed. The only engines that it could not be used on are those that do not have intake manifolds for the fuel such as port fuel-injection and some diesel engines. It might also be necessary to replace some intake manifolds that have baffles with simpler, straighter manifolds to increase the opportunity for thorough mixing of the gasoline vapor and air. Because it is self-regulated by engine demand, the same size valve could be used on a maker's entire line of engines, thereby minimizing production costs. Test data indicates that the valve could be expected to increase fuel economy and torque, to lower emissions and octane requirements, and to improve driveability, while possibly saving the maker (and ultimately the consumer)

36/ National Research Council and National Academy of Engineering, p. 154-156.

about $200 per car. Lower engine maintenance costs and operating expenses, if realized across the fleet, could also be expected to increase buyer interest in new cars equipped with the valve.

When the valve was formally introduced to the automobile and oil industries on October 15, 1980, the Webster-Heise Corporation made an interesting proposal. If offered to grant U.S. automakers a head start by preventing for five years the use of the valve on foreign cars imported to the United States. If accepted, this could be expected to have the effect of shifting buyer interest away from the imports and toward the domestic models. The increased performance and lower operating cost of the modified domestic cars would probably increase their appeal in the marketplace. If that proved to be the case, then it is possible that the Webster-Heise valve could enhance the competitiveness of the U.S. auto industry.

VII. IS THERE A FEDERAL ROLE?

In a market economy, improvements in automotive technology are normally the province of private enterprise. Such innovation is a matter of entrepreneurial decision and risk; it ultimately succeeds or fails in the crucible of the competitive marketplace. This process, to which virtually all products and services are subject, is constant and pervasive. The Federal role, in theory and to a somewhat lesser extent in practice, is largely to be a rational consumer in this market and to regulate the marketplace in such a way that competition operates to the benefit of society. Occasionally, however, the Federal Government intervenes to accomplish certain consensus national goals. There are, therefore, cases both for and against Federal encouragement of the Webster-Heise valve.

Federal options in this matter include (a) no Federal action, (b) Federal laboratory testing of the valve in the wide range of vehicles and circumstances necessary for commercial utilization and publication of the results, and (c) Federal field testing of the valve by installation in a working fleet of Government vehicles over an extended period with published results.

The case for Federal action along the lines of (b) or (c) might be summarized as follows:

1. There is reason to believe that the market is working imperfectly in this case with the result that full testing and introduction of the valve is being prevented or delayed and consumers are being denied its benefits.

2. Significant progress in meeting certain important national goals is being frustrated by corporate timidity or an unfortunate confluence of market forces with

respect to the Webster-Heise technology. The national interests being frustrated are:

a. Fuel self-sufficiency
b. Reduction of severe balance-of-trade deficits
c. Competitiveness of the U.S. auto industry
d. Environmental health and well-being
e. Reduction of inflation

3. The potential social benefits of this technology far outweigh the market rewards to be reasonably expected by auto manufacturers or commercial users of the Webster-Heise valve. For this reason, it is justifiable in theory and in practice that society (through the Federal Government) share in the cost of development and testing.

4. The cost of Federal laboratory or field testing is small relative to the potential benefits. Tests might be conducted on the Postal Service fleet, where a large body of information could be obtained on a wide variety of vehicles. Other Federally sponsored tests might be conducted by the National Aeronautics and Space Administration, the Environmental Protection Agency, the Department of Transportation, and the Department of Energy, all of which have conducted similar tests in the past.

The case against Federal intervention with respect to the Webster-Heise valve might include the following:

1. The market is not working imperfectly in this case. The Webster-Heise technology has been in the marketplace for only two years; substantial testing has occurred and the results are known to a limited extent in the industry; much about the valve remains unknown and corporate decision-making is in progress.

2. All of the claimed societal benefits rest on the assumption that the technology works as claimed and that it would be practically and economically applicable to mass production and use. Similar societal benefits were or could have been argued over the past 50 years for scores of devices which failed or had negative offsets in practical application.

3. Market acceptance of the Webster-Heise technology also rests upon its not being preempted by other technologies designed to achieve similar automotive goals; toward these ends a considerable research effort is currently underway both here and abroad. This is a matter for testing and decision-making in the market place without preferential government intervention.

4. Whether or not the market fully reflects the potential social benefits of this technology, if it works as claimed and is competitively superior to the other approaches, there is more than ample incentive for entrepreneurial venture investment. If the leading automotive and engine makers and users show reticence to begin testing there may also be cause for reticence on the part of the Federal Government to subsidize testing when there are other technologies competing for market acceptance.

APPENDIX I

TECHNICAL ANALYSIS

A. Pre-combustion effects

1. Gasoline Vaporization

Gasoline will burn only as a vapor. For that reason, all engines attempt to vaporize gasoline prior to combustion, sometimes achieving as much as 60 percent vaporization with the rest of the gasoline in the form of droplets ranging in diameter from 20 to 100 microns or more. These liquid droplets, along with the vapor and air, are introduced into the combustion chamber and burn incompletely, often producing detonation (engine "knock"), carbon deposits, high emissions, unequal distribution to and within the cylinders, and lower than optimum fuel economy. Engines that have achieved 60-percent vaporization prior to combustion have done so by using exhaust heat to obtain high temperatures in the intake manifold (over 240 ^{o}F). These high temperatures can increase the vaporization of gasoline by boiling it to the 60-percent level, but they have the associated disadvantage of decreasing volumetric efficiency. Fuel injection is a technique used by the auto industry to increase volumetric efficiency by using cooler air but, because injected fuel has very little time to vaporize and mix with the air in the cylinder, the timing must be retarded with a consequent loss in fuel economy. The optimum solution to this problem is to vaporize the gasoline at low temperatures (around 130 ^{o}F, the ambient temperature of the air entering the intake manifold) so that the negative effects of high temperature are not a factor. This however, had not proven practical prior to the development of the Webster-Heise valve, although it had been demonstrated experimentally by General Motors in single-cylinder engine tests in the mid-1970's. 37/

In order to convert a liquid (such as gasoline) to a gas, a considerable amount of energy is necessary to break the forces that hold the liquid together. 38/ The amount of energy required is determined by the magnitude of the intermolecular forces to be overcome. Generally, the components having higher boiling ranges have higher chemical energy contents. In the case of gasoline, this is complicated by the fact that it has at least 16 different components, each with its own boiling point under standard conditions (Fig. 5). It is not necessary, however, to heat gasoline to its final boiling point in order to achieve full vaporization. As long as the dew point of the gasoline (determined by the air/fuel ratio of the mixture, the fuel composition, and the inlet manifold pressure) is below the manifold temperature, then the fuel can be vaporized and evenly distributed. 39/

37/ William R. Matthes and Ralph N. McGill, General Motors Research Labs, "Effects of the Degree of Fuel Atomization on Single-Cylinder Engine Performance," Society of Automotive Engineers Paper 760117 presented at the Automotive Engineering Congress and Exposition; Detroit, Michigan, Feb. 23-27, 1976.

38/ Paul A. Sanders, Handbook of Aerosol Technology, Van Nostrand: New York, 1979. p. 264.

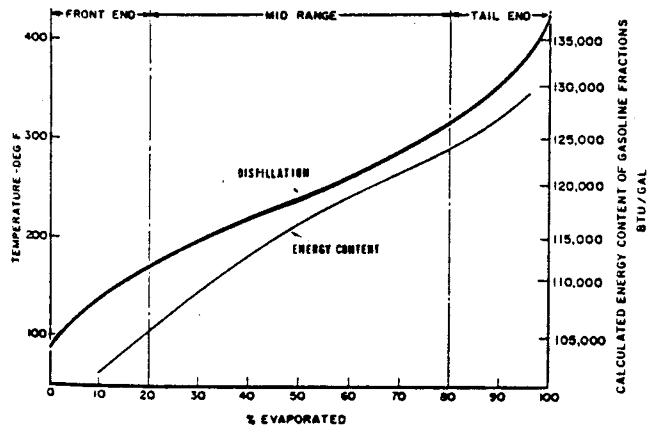
39/ G.A. Harrow. "The Effect of Mixture Preparation on Fuel Economy" in Fuel Economy of the Gasoline Engine: Fuel, Lubricant and Other Effects. Ed. by D.R. Blackmore and A. Thomas (Shell Research Ltd.), John Wiley and Sons: New York, 1977. p. 94.

FIGURE 5. DISTRIBUTION AND BOILING RANGES OF GASOLINE COMPONENTS 40/

Component	Boiling Point in Still Air at One Atmosphere (Degrees Fahrenheit)	Weight (Percent)	Cumulative Evaporation (Percent)
Propane	- 6.62	0.05	.05
Isobutane	-10.94	1.44	1.49
Butane	-31.10	4.79	6.28
Isopentane	82.22	7.59	13.87
Pentane	96.98	8.88	22.75
2-methyl but-2-en	101.48	2.38	25.13
Isohexane	140.54	8.21	33.34
Hexane	155.66	7.13	40.47
Benzene	176.18	2.85	43.32
2, 3 dimethylpentane	193.64	3.45	46.77
Heptane	209.12	4.14	50.91
Toluene	213.08	11.16	62.07
m-Xylene	282.38	15.17	77.24
3-ethyl toulene	322.34	9.08	86.32
Pseudo cumene	336.92	5.03	91.35
1, 3 diethylbenzene	358.52	8.65	100.00

40/ D.J. Boam (National Engineering Laboratory (Glasgow)," A Computer Model of Fuel Evaporation in the Intake System of a Carbureted Petrol Engine," IMECE Conference Publication 1979-9, The Institution of Mechanical Engineering, London, 1979, p. 32.

FIGURE 6. TYPICAL GASOLINE DISTILLATION CURVE 41/



Because the heavier components of gasoline do not vaporize as readily as the lighter ones (because of their higher boiling points), there is a substantial amount of "heavy ends" (approximately 50 percent of the gasoline by weight) which is normally admitted to the combustion chamber as liquid droplets (Fig. 6). There they coat the piston heads and cylinder walls and burn unevenly and incompletely, leading to crankcase dilution and contamination, engine deposits, gum and varnish formation, and spark plug fouling. The liquid gasoline gets past the rings and into the crankcase where it dilutes the oil and reduces its viscosity. The crankcase dilution is aggravated by the low engine operating temperatures associated with cold weather, especially in stop-and-go driving

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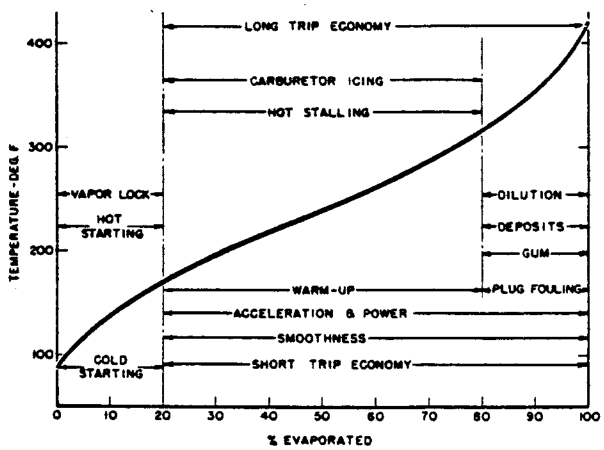
41/ D.E. Foringer (Gulf Reserch and Development Co.), "Gasoline Factors Affecting Fuel Economy," Paper 650427 presented at the API Midyear Meeting, May 1965, p. 243.

where engine temperatures do not reach levels high enough to evaporate the gasoline that is diluting the oil. 42/ This promotes engine wear, poor performance, and high emissions. It has been widely suggested that if the volatility of these heavy ends could somehow be increased, then these negative effects would be greatly diminished. 43/

The importance of vaporization of the fuel to the engine performance is shown in Figure 7. In a standard engine, cold start problems are common and even as it warms up, the engine is subjected to stalling, carburetor icing, dilution, and engine deposits. If the vaporization level were about 95 percent of the intake mixture and the temperature in the intake manifold maintained at a level above 125 °F (both are conditions which apply in Webster-Heise modifications), then the engine should operate in a zone of maximum power, smoothness, and economy under all speed and load demands.

FIGURE 7. EFFECTS OF TEMPERATURE AND VAPORIZATION ON ENGINE PERFORMANCE 44/



42/ Foringer, p. 243.

43/ Ibid., p. 243.

44/ Ibid., p. 243.

The heat energy required to convert gasoline from the liquid to the gaseous state with no temperature change is called the latent heat of vaporization. The heat is transferred by both conduction and convection of energy between adjacent molecules. 45/ Vaporization of gasoline may be accomplished, therefore, by increasing its manifold temperature (as in standard engines) or by lowering the pressure, by increasing the surface area of the droplets by forming more of them and reducing their diameters, and by increasing the heat transfer (as in the Webster-Heise valve). To obtain lower emissions, greater power, lower octane requirements, and greater fuel economy, it is far more effective to reduce manifold pressure and to increase heat transfer to the gasoline rather than to increase temperature.

At standard atmospheric pressure and temperature, some vapor will evolve from gasoline and given enough time the gasoline will evaporate completely. Because the pressure in the intake manifold is far less than one atmosphere (due to the vacuum created in the cylinders by the pumping action of the pistons and by the one-inch pressure drop caused by the double screens), the boiling point of gasoline is lowered substantially. 46/ At the reduced pressure, latent heat is rapidly transferred to the hydrocarbon molecules by the large number of air molecules surrounding each fuel droplet, resulting in partial vaporization. If finely atomized gasoline is heated by the intake air in a zone of lower pressure (the

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45/ C.O. Bennett, Momentum, Heat, and Mass Transfer, McGraw-Hill: New York, 1974, p. 244.

46/ General Motors Corp. Theory and Diagnosis of Chevrolet Carbueretors. Training Manual No. ST339-71, 1971, General Motors Corp.: Detroit, p. 2.

partial vacuum of the intake manifold), it will undergo differential vaporization (rapid vaporization due to the sudden drop in pressure). 47/ This is the process at work in the Webster-Heise valve (Figure 8).

The Webster-Heise valve allows the throttle plate to be closed to a greater degree than in a standard engine at the same speed and load. The valve adds one inch of Hg to the intake manifold vacuum and the throttle can add another 4 to 5 inches for a total vacuum that is 5 or 6 inches higher than standard at the same low speeds or loads. The vaccum decreases as the engine speed increases and, at wide-open throttle, the vacuum difference is reduced to one inch (see Test 6, Summary of Tests) because the vacuum due to throttling is no longer present. A differential of that size reduces the fuel/air mixture density ratio. In a standard engine, this would normally create a small power loss, but in the Webster-Heise modification this facilitates vaporization and is apparently more than offset by a variety of combustion benefits and by greater volumetric efficiency. Although the density effect diminishes with higher speeds and loads as the vacuum decreases, there are marked benefits at low and moderate speeds and loads. These include an effective reduction in compression ratio, contributing to the tolerance for low-octane fuels.

The higher manifold vacuum created by the partial closing of the throttle enhances the vaporization of the fuel. More complete vaporization increases the evenness of fuel distribution to the cylinders and provides a more complete burn. Fuel consumption at a given speed is

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47/ R.E. Collins (Physics Department, Univ. of Houston). Flow of Liquids Through Porous Materials. Reinhold: New York. 1961. p. 247-248.

reduced in near proportion to the density ratio. Lower fuel consumption also reduces exhaust emissions. HC and CO are further reduced because the fuel is more completely vaporized before combustion. The lower effective compression reduces combustion peak temperatures and correspondingly reduces the formation of NOx. Early tests suggest that torque is enhanced by the better vaporization and distribution of the fuel. Further quantification of this effect on work output, engine speed, and fuel requirments would be valuable in assessing the performance of the valve.

According to the Webster-Heise Corporation, the valve has several features that are unique, without any of which it would not be effective. The valve, in self-regulated response to engine demand, moves up and down in the intake manifold. This is a critical characteristic because without the ability to sufficiently vary the screen area exposed to the air/fuel flow as needed there would be a restriction that would impede the flow of air and fuel and would result in a power drop. For decades single fixed screens have been tried, without success, to increase fuel vaporization, but because they were fixed they were optimized for only one power requirement. For all other states they actually constituted restrictions that were worse than no screen at all. Because there was only one screen involved, there was also no control over the scale or intensity of the turbulence produced.

The Webster-Heise valve differs from these early attempts in that it consists of two stainless steel screens pressed together, a coarse stainless steel mesh (# 50) followed immediately by a fine mesh (# 120). The openings in the two adjacent screens constitute a series of thousands of micronozzles that force the liquid into small droplets (well under

10 microns in diameter) which quickly and totally vaporize within a few inches of the outer screen because of three improvements in the quality of the air that occur when it passes through the double screens:

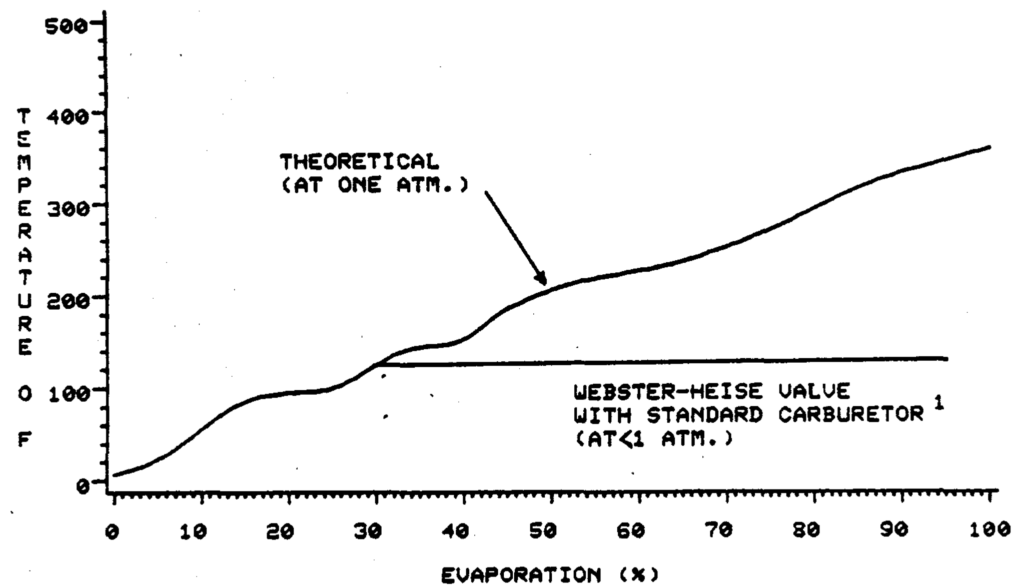

FIGURE 8. EVAPORATION OF GASOLINE

*Differential vaporization begins at 125 °F because the screens in the valve act as a nozzle matrix that creates low pressure streams of turbulent, high-energy air and atomized fuel. The air temperature in the intake manifold does not exceed 130 degrees F. Also note that vaporization with the W-H valve takes place in a fraction of a second whereas the theoretical evaporation curve is not time limited.

Source: Webster-Heise Corporation

(1) more internal energy (from impingement and compression)

(2) lower pressure (because of the Bernoulli Effect resulting from the air passing through the nozzles); and

(3) greater intensity of turbulence (due to the small orifice sizes).

The screens must be tightly pressed together or the scale of turbulence will not be great enough and the rapid vaporization effect will be lost. The vaporization effect diminishes rapidly, and may be lost altogether, if the mesh sizes are varied by more than a few numbers. Very little variation in design can be tolerated in either case if maximum vaporization is to occur. Recent experiments suggest that even greater results may be obtained if one of the screens is rotated 45 degrees (in the same plane) with respect to the other so that the openings of the two screens are completely random and not in registration.

Another important factor in the operation of the valve is the "radial jump space" near the bottom of the valve. The air and fuel droplets are accelerated as they pass through the jump space and impinge on the vertical screens and are compressed as they enter the matrix, at which time much of their kinetic energy is converted into internal energy.

Flow through double screens of different mesh sizes is the equivalent of flow through a number of orifices or nozzles in parallel (a nozzle matrix). 48/ The pressure drop across the screens is controlled by a vacuum valve at a level of about one inch of mercury, although the pressure drop on the outer surface of the screen may be much greater (for

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48/ Robert H. Perry and Cecil H. Chilton. Chemical Engineers Handbook, Fifth Edition, McGraw-Hill: New York, 1978. p. 5-37.

a very short distance downstream from the valve) because of the relatively high vacuum that is created between each of the nozzle jets. The change in pressure is apparently sufficient to permit differential vaporization. Although the one-inch pressure drop is a slight restriction, it has the effect of reducing fuel consumption. The small negative effect that the one-inch pressure drop has on torque is more than offset by the greater density and combustibility of the charge to the cylinders (cool air mixed thoroughly with gasoline vapor) and the improved distribution to the weak cylinders. The greater mass of air available for expansion and the more favorable timing result in a net increase in available torque, despite the slightly higher vacuum.

Droplet size increases with the square of the orifice diameter. 49/ The orifices in the Webster-Heise valve are exceptionally small, .0046 inches square or smaller. An orifice this size induces three times as much heat transfer as an orifice .008 inches in diameter. 50/ Because the air is moving faster than the fuel droplets inside the valve, its high velocity can readily penetrate the liquid as it forms a film on the inner screen, producing the necessary turbulence and energy transfer to finely atomize the fuel. 51/ Upon exiting the outer screen, transverse shear forces are set up by the intersecting sprays, which work in conjunction with the rapid drop in pressure to cause the fuel to vaporize. Be-

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49/ K. Masters, Spray Drying, John Wiley and Sons: New York, 1976, p. 184.

50/ Perry and Chilton, p. 18-61.

51/ Ibid., p. 18-64.

fore passing through the screen, the fuel is deposited as a film on the coarse mesh openings by turbulence within the valve. It is then accelerated through the smaller micronozzles (fine mesh), and then sheared by the other existing streams on the outside of the valve. This is important because only a slight reduction in droplet size causes a marked increase in fractional evaporation. 52/ Small droplets evaporate virtually instantaneously, and a large proportion of the evaporation is accomplished during the deceleration of the droplets. 53/ The diameters of the droplets exiting the valve are uniformly very small, probably less than 20 percent the size of the smallest droplets produced by the carburetor. Because of the droplet small diameters and the conditions created both inside and outside of the valve, most of the gasoline apparently vaporizes almost instantly (within 0.2-2.0 inches from the valve) at temperatures above 125^{o} F.

The combined effect of internal circulation, oscillation, surface distortion, acceleration, deceleration, shearing, and depressurization, along with high intensity of air turbulence results in vaporization rate that is probably close to but not quite 95 percent. 54/

During experimentation with different screen sizes, it was found that only the combination of the #50 interior coarse mesh and the #120 exterior

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52/ K. Masters, p. 299.

53/ Ibid., p. 308.

54/ Ibid., p. 296.

fine mesh would achieve the differential vaporization effect, probably because the intensity of turbulence is increased proportionately more than the scale of turbulence is decreased. These two meshes produce a reverse taper (wider spray) orifice with an exit diameter of at most .0046 inches. This is much smaller than conventional state-of-the-art micronozzles which have diameters as small as .008 inches. These valve-actuator combinations produce a very fine droplet size. 55/ Because the heat and mass transfer value that results from dispersion by the Webster-Heise valve is exceedingly high $(1/.0046)^2$ or 47,260 (a gain of about 200 percent over a standard engine), ultra-fine droplets are favored. 56/ The smallest commercial aerosol orifice is only $(1/.008)^2$ or 15,625 (a transfer rate one-third that of the Webster-Heise rate). Because the orifice diameter is so small, the air stream is rotated and internally mixed within the nozzle and mixed again externally as it emerges from the nozzle, resulting in very fine sprays even at low feed rates and pressures. 57/ The Webster-Heise valve can operate with a smaller orifice because the air is accelerated by passing through the double down-tube and by the greater pressure differential between the intake manifold and the interior of the valve.

Turbulence appears to be essential to the high speed of vaporization in the Webster-Heise valve. The high friction produced by the passage of air and gasoline through these screens results in an irreversible thermo-

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55/ Sanders, p. 105.

56/ Perry and Chilton, p. 18-61.

57/ Masters, p. 16.

dynamic process in the intake manifold of an operating engine. 58/ Nonequilibrium thermodynamics (the extension of classical thermodynamics to transport systems) is an area of science that is not yet well understood. It is clear, however, that this kinetic energy is converted to latent heat by high friction flow, thereby increasing the internal energy of the air to the point where it can cause a change of state of the gasoline in an environment of low pressure and high turbulence.

Turbulence has long been known to be essential to rapid vaporization. It has long been known that turbulence can be effectively used to homogenize fluid mixtures and to accelerate chemical reactions. 59/ The mass transfer takes place through the relatively fast process of eddy diffusion and can result in values 100,000 times that of normal molecular diffusivity. 60/ A five-percent increase in turbulence in the air can increase the rate of vaporization 20 to 30 percent. 61/ The Webster-Heise valve creates turbulence that is apparently over 200 percent higher than standard and may yield potential increases in the vaporization rate of 800 percent or more.

Turbulent flows are always dissipative because viscous shear stresses perform deformation work on the gasoline which increases its

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58/ Donald D. Fitts (University of Pennsylvania Chemistry Dept). Nonequilibrium Therodynamics: A Phenomenological Theory of Irreversible Processes in Fluid Systems, McGraw-Hill: New York, 1962. p. 1.

59/ Bennett, p. 1.

60/ Perry and Chilton, p. 14-5.

61/ H.R. Pruppacher and R. Rasmussen (Univ. of California. Dept. of Atmospheric Sciences). "A Wind Tunnel Investigation of the Rate of Evaporation of Large Water Drops Falling at Terminal Velocity in Air." Journal of the Atmospheric Sciences. July 1979. Vol. 36. p. 1258.

internal energy at the expense of the kinetic energy of the turbulence. 62/ In other words, the rapid movement of the air molecules and gasoline droplets are converted to internal heat energy upon deceleration after exiting the Webster-Heise valve. The intensity of the turbulence shears the main flow after it passes through the Webster-Heise screens.

The most important characteristic of turbulence is its ability to transport or mix momentum, kinetic energy, and contaminants such as heat, particles, and fluids. 63/ The rate of transfer and mixing are several orders of magnitude greater, therefore, than the rates due to molecular diffusion. 64/ The diffusivity of turbulence is the single most important feature as far as automotive applications are concerned because it increases the transfer rates of heat and momentum, both of which result in vaporization at temperatures well below the normal boiling point. 65/ In the case of the Webster-Heise valve, this takes place at a temperature slightly above 125 ^{o}F (the dew point of gasoline in an intake manifold). The ambient intake manifold temperature is about 130 ^{o}F if the exhaust heat recirculation normally used in standard engines is removed and about 240 ^{o}F or more if it is employed.

62/ H. Tennekes and J.L. Lumley. A First Course in Turbulence. MIT Press: Cambridge, 1972. p. 3.

63/ Ibid., p. 7

64/ Ibid., p. 7.

65/ Ibid., p. 2.

The fact that turbulence has not been used to better effect in automobile engines illustrates the degree to which turbulence theories are not understood. As Tennekes and Lumley point out: 66/

> Randomness and nonlinearity combine to make the equations of turbulence nearly intractable; turbulence theory suffers from the absence of sufficiently powerful mathematical methods. This lack of tools makes all theoretical approaches to problems in turbulence trial-and-error affairs. Nonlinear concepts and mathematical tools have to be developed along the way; one cannot rely on the equations alone to obtain answers to problems. This situation makes turbulence research both frustrating and challenging: it is one of the principal unsolved problems in physics today.

Perhaps the most important point made by Tennekes and Lumley is the following: 67/

> This book has been designed to get this point across. In turbulence, the equations do not give the entire story. One must be willing to use (and capable of using) simple physical concepts based on experience to bridge the gap between the equations and actual flows. We do not want to imply that the equations are of little use; we merely want to make it unmistakably clear that turbulence needs spirited inventors just as badly as dedicated analysts.

Screens have been used in other applications where similar conditions exist (but which do not involve combustion) and where similar effects were desired: 68/

66/ Tennekes and Lumley, p. 2-4.

67/ Ibid., p. 4.

68/ Alan Pope and Kenneth L. Goin (Sandia Corp). High-Speed Wind Tunnel Testing. John Wiley and Sons: New York, 1979. p. 101.

> ...At large pressure-drop coefficients, turbulence may be caused by screens and it is recommended that several low-pressure-drop screens are preferable to a single high-pressure-drop screen. This is the practice normally followed in blowdown tunnel design.

The intake manifold equipped with a Webster-Heise valve is essentially a minute "wind tunnel" with a one-inch pressure differential or more and an ambient temperature of about 130 ^{o}F. It has been observed that: 69/

> Uniform fluid distribution is essential for efficient operation of chemical processing equipment such as contactors and reactors, mixers, burners, heat exchangers, extrusion dies, and textile-spinning chimneys. To obtain optimum distribution, proper consideration must be given to flow behavior in the distributor, flow conditions upstream of the distributor, and flow conditions downstream of the distributor...
>
> A non-uniform velocity profile of turbulent flow through channels or process equipment can be smoothed out to any desired degree by adding sufficient uniform resistance, such as perforated plates or screens across the flow channel.

Droplet breakup is accomplished by the Webster-Heise valve through three separate but related processes: 70/

1. The impingement of the fuel and the air, after accelerating across the radial jump space, on the screens.
2. A pressure drop due to the presence of high-friction nozzles (the combined screens).

69/ Perry and Chilton, p. 5-49.

70/ Perry and Chilton, p. 18-61.

3. The high intensity of turbulence caused by the micronozzle effect of the adjacent nonuniform screen openings.

In all of these, the density of the air involved is an important consideration. Perry and Chilton found that when a solid jet of liquid (in this case gasoline) is being impinged upon by a gas (air), its relative velocity assumes a much greater importance than it does without impingement. 71/ Generally, there is a strong decrease in droplet size with increasing gas density. It is important to note that in an engine modified with a Webster-Heise valve, the intake manifold temperature may be as low as only 130 ^{o}F versus the 240 ^{o}F that is normal in standard engine (the extra heat recirculation can be removed because it is no longer necessary for the vaporization of gasoline). Thus, the cool air is much denser and capable of greater droplet size reduction because of its greater dynamic force. 72/

There are four flow regions associated with a valve of this type: 73/

1. Region of flow establishment--a short region whose length is about 5 nozzle diameters or slot heights (for a slot of infinite width). The fluid within the cone or core of same length has a velocity about the same as the initial discharge velocity.

2. A transition region that extends to about 8 nozzle diameters, slightly less for slots.

3. Region of established flow--the principal region of the jet, extending to about 100 nozzle diameters or about 2000 slot heights.

71/ Ibid., p. 18-59 -- 18-61.

72/ Masters, p. 212.

73/ Perry and Chilton, p. 18-49.

> 4. A terminal region where the residual center-line or maximum velocity reduces rapidly within a short distance. For air jets, the residual velocity will reduce to less than 1 ft./sec., usually regarded as still air.

Virtually all of the droplet breakup (and much of the vaporization) probably occurs within the first one-half inch after exiting the outer screen (113 nozzle diameters times a nozzle diameter of .0046 inch). The time required for this phase dispersion is about 13 milliseconds. 74/

The rapid rate of vaporization in the Webster-Heise valve is highly dependent upon the unusually high internal energy of the air and the rate at which it can be transferred to the fuel droplets which also are subject to an increase in their own level of internal energy. 75/

Pierce has shown that: 76/

> For an adiabātic flow with zero shaft work, the changes in system directed kinetic energy will result in system temperature changes with changes in the internal energy content and distributions in the various degrees of freedom...
>
> As the gas is decelerated, there is an energy exchange between the directed kinetic energy of the gas stream and the internal energy of the gas itself. Assuming an adiabatic stagnation, then all of the directed kinetic energy must manifest itself as an increase in internal energy. The stagnation can occur so rapidly, however, that the vibrational degree of freedom may not accept its share of this directed kinetic enegy as rapidly as necessary to

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74/ Perry and Chilton, p. 18-60.

75/ Sanders, p. 146.

76/ Felix J. Pierce (Virginia Polytechnic Institute Department of Mechanical Engineering). Microscopic thermodynamics: The Kinetic Theory and Statistical Thermodynamics of Dilute Gas Systems. International Textbook Company: Scranton, 1968, p. 284-303.

> insure that equilibrium exists. Then since the total energy is constant, the active degrees of freedom must accept more energy than equilibrium requires to compensate for the deficiency in energy content of the lagging degree of freedom...
>
> In the flow through the shock front there is a sharp reduction in the directed kinetic energy of the gas. Assuming adiabatic flow along stream tubes, then this directed kinetic energy must be transferred to the gas molecules and manifest itself as intrinsic or internal energy of the gas. Since the vibrational degree of freedom is slow in acquiring its share of this new energy, a non-equilibrium situation can occur where initially virtually all this transformed directed kinetic energy is absorbed by the active translational and rotational degrees of freedom, and almost none is absorbed by the inert vibrational degree of freedom.

Another very important mechanism acting concurrently with the turbulence the Webster-Heise valve is differential vapor recoil. This principle, despite its dramatic effects on vaporization (especially at low temperatures), has not been well understood outside of research laboratories. 77/ The Webster-Heise valve is apparently the first application of this principle to automotive use. Palmer has described the effects of vapor recoil on the evaporation rate: 78/

> A mechanism for inducing spontaneous convection, that of instability induced by differential vapour recoil, was first noted and correctly interpreted by Hickman in 1952 but has since attracted surprisingly little attention despite its dramatic effect on the evaporation of liquids at pressures below 1 Torr.

77/ Harvey J. Palmer (Distillation Research Laboratory of the Rochester Institute of Technology). "The Hydrodynamic Stability of Rapidly Evaporating Liquids at Reduced Pressure." Journal of Fluid Mechanics, Vol. 75, Part 3, 1976, p. 487.

78/ Ibid., p. 487-489.

> Hickman (1952) has shown that an increase as high as 20-fold in the liquid evaporation rate may be enjoyed if the interface is disrupted by differential vapour recoil. The onset of such convection appears as a sharp transition from a relatively quiescent evaporating liquid surface as the presure above the liquid is decreased.
>
> Because mass must be conserved, the change in fluid density during evaporation results in a discontinuity in both the fluid velocity normal to the interface and the rate of transport of linear momentum across it. Momentum must also be conserved. Therefore the discontinuity in velocity results in a downward force on the interface (vapour recoil) which increases with evaporation rate and with an increase in the density ratio of the liquid and gas phase. Since the density of the gas phase is linearly proportional to the pressure, the magnitude and, thus, the importance of this vapour recoil force increase markedly as the pressure is reduced.

If a liquid in contact with its own vapor is evaporated at low pressure, interfacial heat transfer and evaporation rates can be increased dramatically by the onset of interfacial convection by differential vapor recoil. 79/ The resulting discontinuity produces a downward force on the interface (vapor recoil) which increases with the increasing evaporation and the decreasing pressure. Palmer has demonstrated that this mechanism dominates interfacial behavior for evaporation into a partial vaccum. 80/ This same research provides the explanation for the likelihood that the Webster-Heise vaporization rate is probably on the order of 95 percent rather than 100 percent (compared to approximately 60 percent prior to combustion in

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79/ Harvey J. Palmer (University of Rochester). "Enhanced Interfacial Heat Transfer by Differential Vapor Recoil Instabilities." International Journal of Heat and Mass Transfer, January 1981, p. 117.

80/ Ibid., p. 118.

warmed-up standard engines). Experiments and stability analyses have shown the extreme sensitivity of the vapor recoil mechanism to interfacial contamination such as engine oil and water (from condensation). 81/ As a result, the interface (between the liquid and vapor phases) will still develop some "torpid" patches about 5 percent of the time because evaporative fluxes are suppressed wherever the less volatile material accumulates on the surface. 82/

Phase changes of fluids in pipelines have been observed for many years. In pipelines, this is an unwanted effect, but it serves as a useful analogy in explaining the way in which gasoline flashes to vapor upon exiting Webster-Heise valve and entering the intake manifold, which is very much like a pipeline in that it is a tube transporting a liquid which is subjected to pressure changes. In a pipeline, differential vaporization occurs because of the rapid relative velocity of the gas phase. 83/ As the saturated liquid flows through the pipe, friction (as in the Webster-Heise screens) causes a pressure drop in the direction of flow followed by vaporization. 84/ The mass transfer rate from the gas back to the liquid phase is zero (or very close to to it). 85/ The

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81/ Ibid., p. 118.

82/ Harvey J. Palmer (University of Rochester). "Spontaneous Convection in Organic Liquids Evaporating at Reduced Pressures." The Petroleum Research Fund Grant#9146-AC7, October 30, 1980, p. 1.

83/ Mohammed Anis and Paul Buthod. (University of Tulsa, Department of Chemical Engineering). "How Flashing Fluids Change Phase in Pipelines." The Oil and Gas Journal. June 24, 1974. p. 150.

84/ Ibid., p. 151.

85/ Ibid., p. 151.

vapor is swept away without contributing to the equilibrium composition, promoting further vaporization. The cooling effect accompanying the pressure drop is much less than would be predicted in an equilibrium model and apparently has the effect of increasing the volatility of the liquid. 86/

2. Mixing

Mixing is a critical part of the pre-combustion phase of the operation of a gasoline-powered engine. It has been somewhat neglected in current engine designs in which only limited mixing occurs due to the presence of baffles and ridges in the intake manifolds. This not only is a relatively ineffective way to mix air and gasoline, it often has a negative effect in that it provides numerous opportunities for the liquid gasoline issuing from the carburetor to collect on the walls of the intake manifold.

Harrow has described the compromises that current engines represent because of imperfect mixing:

> ...Traditionally, at full throttle, part of the latent heat of vaporization of the fuel is used to chill the mixture entering the engine and thus to increase the maximum power. In the absence of a perfect mixture preparation system which will provide both a chilled mixture and a fully atomized fuel, engine inlet manifolds have to cope with mixtures of liquid and vapour. A consequence of this need to combine several functions is that an engine mixture preparation system is a package which represents the manufacturer's best compromise between the conflicting requirements of power, emissions and economy. The result is invariably sensitive to minor changes in the carburation and inlet system geometry,

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86/ Anis and Buthod, p. 151.

> which can give an improvement for one type of engine condition at the expense of performance in another. 87/
>
> The engine manufacturer tries to ensure uniform distribution of fuel between the cylinders by providing a hot spot to transmit exhaust heat to the mixture and by drawing some of the inlet air to the engine from around the exhaust manifold. The inlet manifold is also designed to permit a certain amount of liquid fuel to flow freely to the cylinders. These procedures are not normally very effective, and almost invariably some fuel maldistribution does occur. 88/

A homogeneous mixture of gasoline vapor and air is the ideal condition for the inlet charge of a gasoline engine. 89/ Vaporization greatly improves the mixing rate but, even in high-heat engines, the charge is still far from homogeneous by the time it reaches the entrance to the cylinders. This is because insufficient turbulence is available to cause the gasoline vapor molecules and air molecules to associate completely. It is compounded by the fact that many intake manifolds are not sufficiently large to permit good mixing.

The Webster-Heise valve, by design, forces the gasoline vapor and air to mix thoroughly within a short distance from the outer screen. The high turbulence and shearing forces subject both components to an intense mixing process. Because the gasoline is in a vaporized or finely atomized state, it is far less likely to impinge and recondense downstream in the intake manifold. To reduce this possibility, all baffles and other

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87/ Harrow, p. 89.

88/ Ibid., p. 93.

89/ J.R. Goulburn (Queen's University) and D.W. Hughes (New University of Ulster). "Mixing of Vaporized Petrol and Air in Automobile Inlet Systems." In Fuel Economy and Emission of Lean Burn Engines, Institute of Mechanical Engineers Conference Publication 1979-9, June 12-14, 1979. p. 97.

other obstructions are removed to provide a straight and clear path to the intake valve for each cylinder.

The mixing principles employed in the Webster-Heise valve have been known for some time. As Goulburn and Hughes, based on work by Ashley, have observed: 90/

> There are two important principles: break the stream down into a series of smaller streams to speed up mixing and break down stratification patterns; then pass the streams across and through one another to redistribute major stratification patterns. Multiple jets tend to overcome two undesirable characteristics of all of the natural mixing means, which are a relatively unmixed core inside a well mixed outer envelope, and insufficient turbulence.
>
> A design of mixer was produced which met the above criteria and had the added advantage that the heat transfer fins in the vaporizer could, with some modification, also be used to produce a series of jets of mixture directed so that adjacent layers of jets have an interface where fluid shearing will occur. Consider a vaporizer with horizontal fins, and consider one flow passage between the fins. At the end of the passage the flow encounters vertical deflector tabs positioned at 45 degrees to the flow turning the flow to the left (say). The flow passages immediately above and below will have deflector tabs set as 45 degrees to the flow, but turning the flow to the right. The two layers of flow will then, at their interface, be shearing across each other at 90 degrees.

Virtually the same conditions exist in the Webster-Heise valve.

The benefits of improved mixing have been described by Harrow and are well worth considering in the case of the Webster-Heise valve. 91/

90/ Ibid., p. 100.

91/ Harrow, p. 115.

(1) The effect of mixture quality on fuel economy is significant and increases in importance the weaker the mixture strength becomes. It is of particular importance for smooth engine operation under transient conditions.

(2) In multi-cylinder engines, good mixture quality eliminates intercylinder fuel maldistribution and allows the carburetor to be tuned to the maximum-economy mixture strength.

(3) Under cold running conditions, good mixture quality allows minimal use of the choke, thereby reducing short-trip fuel consumption.

(4) With a perfect mixture preparation system, at least part of the engine power could be controlled on mixture strength alone. This would significantly improve part-load fuel economy.

(5) Many devices exist for improving mixture quality. They improve fuel economy, however, only if the mixture strength and spark timing are adjusted correctly to exploit the benefits that they confer.

3. Distribution

Fuel distribution in conventional engines is a problem that is widely recognized. For efficient combustion and smooth engine operation, the air and fuel must be thoroughly and uniformly mixed, delivered in equal quantities to each cylinder, and evenly distributed within each cylinder. 92/ It is generally acknowledged that the best way to achieve this is through a homogeneous charge: 93/

> The process whereby the gasoline fuel and air are metered in the desired proportions and then mixed has been isolated as one of the key elements in making improvements in engine combustion, hence in efficiency and products of

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92/ F.J. Marsee and R.M. Olree (Ethyl Corp). "Distribution Factors That Influence Emissions and Operation of Lean Burn Engines." Fuel Economy and Emissions of Lean Burn Engines, Automobile Division of the Institution of Mechanical Engineers, I Mech E HQ, June 12-14, 1979, p. 129.

93/ Goulburn and Hughes, p. 97.

> combustion. It has been conclusively established that a homogeneous mixture of gasoline and air is the best condition for the inlet charge of a gasoline engine...

In actual practice, however, the mixture in the intake manifold (even with the addition of heat) is not completely vaporized. As a result, the quality and quantity of the fuel charge reaching the cylinders vary considerably. 94/ Because this distribution is unequal, some cylinders produce more power than others and some will have a greater tendency to detonate than others. 95/ If the carburetor is adjusted to provide an adequate mixture to the weak cylinders, then the other cylinders will receive a mixture that is far too rich. The industry has compromised, therefore, by accepting weak and rich cylinders in order to obtain sufficient performance from the other cylinders (Fig. 9). Unfortunately, these extreme cylinders produce a number of undesirable effects. The rich cylinders receive too much fuel which results in incomplete combustion and high hydrocarbon (HC) emissions because there is insufficient air available to burn all of it. The lean cylinders, in contrast, receive sufficient air but are relatively starved for fuel, and the resulting combustion pressures are so low that little useful work is done on the crankshaft. NOx formation is likely in these cylinder because of the relative abundance of oxygen and because the nitrogen is subjected to high heat levels for a comparatively long time due to the long duration of the primary flame.

94/ Toboldt and Johnson. Automotive Encyclopedia. Goodheart-Willcox: South Holland, Illinois. 1977. p. 265.

95/ Ibid., p. 265.

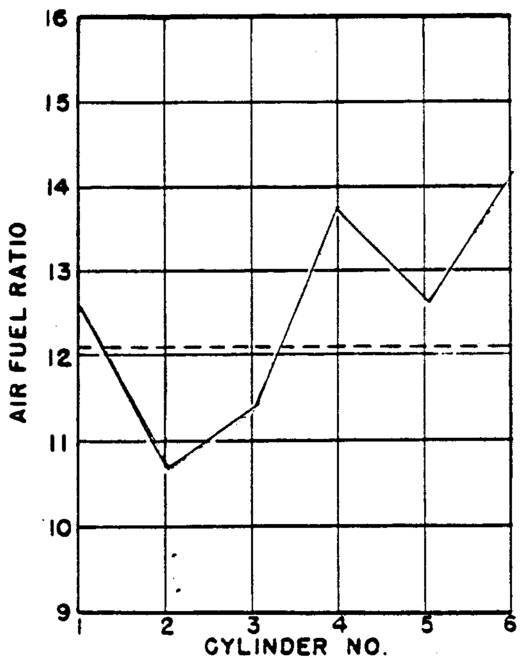

Figure 9. Variation in the air/fuel ratio from cylinder to cylinder. 96/

96/ Toboldt and Johnson, p. 266.

There are several reasons for these variations in distribution. 96/ When the throttle valve of the carburetor is partly open (as it almost always is except at full throttle), the flow of air and fuel is deflected to one side (Fig. 10). The choke valve can also have a similar effect. Even more important is the fact that the heavy components of the air/fuel mixture have greater inertia than the lighter ones. Consequently, the heavy components move past the branches of the manifold. The cylinders supplied by those branches, therefore, receive too many light components (which burn rapidly) and too few heavy components (which contain most of the energy). This problem is shown in Figure 11. For the same reasons, some cylinders will receive more tetraethyl lead (or other negative catalysts) than others. Those cylinders receiving the leanest mixture, the lightest gasoline components, and the least amount of negative catalyst (such as tetraethyl lead) will have the greatest tendency to knock. 97/ The variation betwen minimum and maximum cylinder pressure on the power stroke in a typical six-cylinder engine is on the order of 185 pounds per square inch (psi), with two cylinders delivering the minimum (125 psi) and only one delivering the maximum (310 psi). 98/ The addition of multiple barrels to the carburetor reduces to some extent the variations in cylinder pressure due to poor distribution but does not eliminate them.

96/ Toboldt and Johnson, p. 265.

97/ Ibid., p. 266.

98/ Ibid., p. 266.

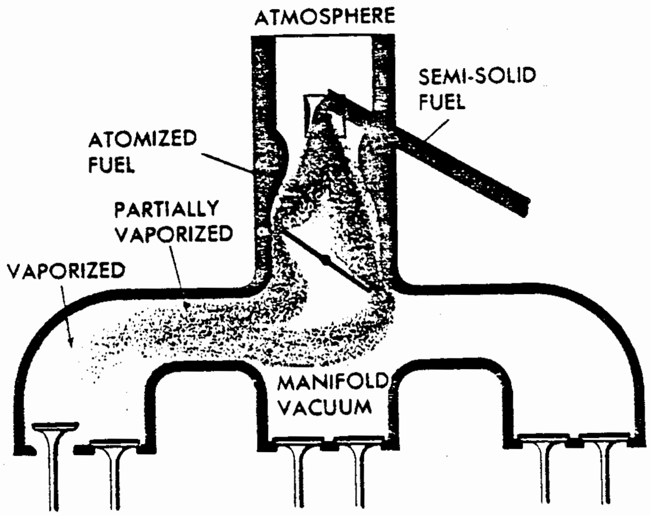

Figure 10. Maldistribution resulting from deflection by the throttle plate. 100/

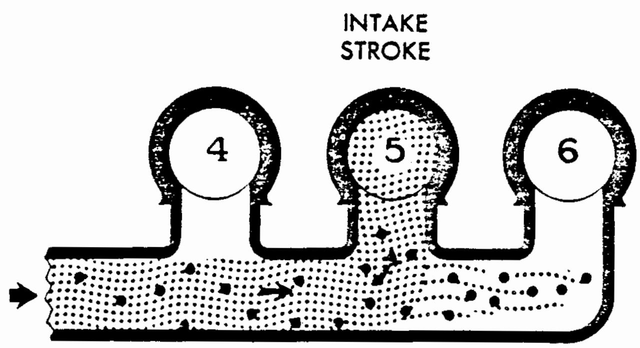

Figure 11. Maldistribution results from heavy components of gasoline flowing through to end of manifold rather than entering branches. 101/

100/ Toboldt and Johnson, p. 266.

101/ Ibid., p. 266.

The distribution problem has been described by Toboldt and Johnson:

> The purpose of a carburetor is to deliver a metered amount of atomized fuel mixed with air, to the manifold. However, regardless of how well mixed and vaporized the fuel mixture is as it leaves the carburetor, its characteristics are changed as it passes through the manifold. Cold surfaces in the manifold will cause some of the vaporized fuel to condense, and changes in direction of flow will, through inertia, cause some portions of the mixture to settle out. These conditions have been observed by using glass manifolds. 102/
>
> The problem is further complicated by the characteristics of the fuel itself. Formerly, when the fuel was highly volatile, the problem was not so difficult. With today's fuels, which are relatively nonvolatile, it is necessary to supply heat to obtain better vaporization and more equal distribution of the fuel to each cylinder. 103/

One of the ways the industry has used to avoid quantity distribution problems is fuel injection. This approach delivers a precise amount of fuel to each cylinder and injects it into the cylinder separately from the air flowing through the intake manifold. This system eliminates the need for manifold heat and permits lower intake temperatures, hence more volumetric efficiency. Fuel injection has its own associated problems, however, including higher emissions, lower fuel economy, and more difficult tuning. Because the gasoline is injected into the cylinder as a liquid rather than as a vapor, the quality of distribution is very low and more time is needed for the heat in the cylinder to partially vaporize the gasoline. As a result, the spark must be retarded severely with a con-

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102/ Ibid., p. 266.

103/ Ibid., p. 268.

siderable loss of fuel economy (the power stroke is partly over before combustion begins). 104/ Retarding the spark does, however, reduce NOx emissions but not HC or CO emissions. The Webster-Heise valve has been shown to reduce all three simultaneously.

The effect of quality distribution on HC emissions has been described by Marsee and Olree: 105/

> ...Quality is indirectly measured by measuring its effect on HC emissions and HC turn-up point as the mixture is leaned. Poor mixture quality at lean mixtures leads to slow flame propagation and the extinguishing of combustion as the pressure and temperature decrease with the descending piston. Poor quality also leads directly to increased HC emissions as some portions of the charge may be too lean to burn.

The Webster-Heise valve is designed to address, through charge conditioning, the distribution shortcomings of both the standard carburetion and fuel injection approaches. The advantage over standard carburetion is apparently a result of the elimination of two long-associated problems: (1) incomplete vaporization of the fuel and (2) incomplete mixing with the intake air.

The controlled turbulence created by the Webster-Heise valve (but lacking in a standard engine) forces the air and vaporized fuel to mix to a much greater extent than would otherwise be possible. Quantity distribution at idle is an especially difficult problem in a standard en-

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104/ David N. Hwang (Ford Motor Co.). "Fundamental Parameters of Vehicle Fuel Economy and Acceleration." Automotive Fuel Economy. Society of Automotive Engineers, Warrendale, Pa., 1976, p. 299.

105/ Marsee and Olree, p. 129.

gine because of the low rate of flow (the throttle valve is almost completely closed). 106/ With the Webster-Heise valve, however, the combination of more complete vaporization and better mixing apparently permit idle speeds to be halved.

The advantage of the Webster-Heise valve over fuel injection is a direct result of the elimination of liquid fuel in the cylinders. By providing a central injection point for a substantially vaporized and thoroughly mixed fuel-air mixture, the quantity distribution problem that fuel injection addresses is effectively eliminated, as measured in the test at Ethyl (see Test 1, Summary of Tests). Just as importantly, the quality distribution is much greater with the Webster-Heise valve because only completely mixed fuel vapor and air reach the cylinder, as opposed to the liquid fuel that is in injected separately by fuel injection. With the Webster-Heise valve, the spark can be advanced considerably to obtain maximum fuel economy (including lower pumping losses) and lower emissions without sacrificing the power gains available through fuel injection.

4. Volumetric Efficiency

One of the reasons that no engine is ever 100 percent efficient is the difficulty of getting a full charge of combustible mixture into each cylinder. A theoretically full charge does not reach the cylinder because of restrictions in the intake manifold, atmospheric temperature, valve timing, and other factors. 107/ Volumetric efficiency is the ratio

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106/ Marsee and Olree, p. 132.

107/ Toboldt and Johnson, p. 95.

of the charge actually taken in per cycle to a complete charge. This ratio is very sensitive to heat (because it lowers the density of the incoming air) and atmospheric pressure (because the pressure difference between the air inside the cylinder and the air outside will determine the volume of air admitted to the cylinder).

The importance of additional air in raising the power output of an engine has been understood since 1902 when Louis Renault patented the supercharger. This device compressed the air, using a pump dirven by the engine, to force more air into the cylinders. Even though superchargers are effective in raising power levels, they do so at a considerable loss in fuel economy due to the additional demands on the engine to drive the pump. They have generally been abandoned in favor or turbochargers, which use the pressure of exhaust gases to compress the intake air. While they have proven to be more satisfactory than superchargers, they are an expensive and relatively fuel inefficient means of boosting power outputs on gasoline-powered engines.

The Webster-Heise valve accomplishes much of the same effect as superchargers and turbochargers without increasing engine loads or pumping losses. (Torque gains of as much as 20 percent were recorded in Test 5, Summary of Tests). This is accompanied by removing the high intake manifold temperatures, which is currently used by automobiles manufacturers to increase vaporization rates but which appears to be unnecessary when a Webster-Heise valve is used. Because incoming air reaches the intake valve at 130^{o} F rather than 240^{o} or more, its density is much greater. In practical terms, this means that more air is available to complete combustion and to expand upon combustion, creating more pressure on the pistons immediately after top-dead-center. This result in substantially more torque. Because there is more air mass to expand after combustion, pressure is also exerted for a longer duration during the power stroke when the crank angle is most advantageous (between 0^{o} and 90^{o}). It should be noted, however, that substantial torque gains may be possible even if the heat is not removed on the Webster-Heise system. Torque increases of up to 40 percent may be obtainable (as shown in Test 6, Summary of Tests), and these gains are very likely due to the improved distribution and the greater pressures that are created in what would othewise be the weak cylinders.

The benefits of lower intake manifold temperatures are readily apparent. Brake specific fuel consumption and engine coolant temperatures are both reduced. 108/ Based solely on fuel consumption considerations, the optimum intake manifold temperature at rated power conditions is 130^{o} F for gasoline 109/ (5^{o} F over the dew-point temperature of 125^{o} F). This is the same approximate manifold temperature that is maintained with a Webster-Heise valve.

108/ R.R. Sekar (Cummins Engine Co.). "A Primer of Charge Air Cooling." Society of Automotive Engineers, Automotive Engineering, May 1982. p. 31.

109/ Ibid., p. 31.

B. Combustion effects

A. Combustion Stoichiometry

The ideal combustion is stoichiometric, meaning that there is no excess gasoline and no excess air. This condition, in which the ratio of air to gasoline is 14.7 to 1 by weight, produces the hottest flame and the lowest emissions. 110/ The maximum temperature peaks and expansion pressures occur when the combustion air is 100 percent of stoichiometric (neither too rich nor too lean), giving further evidence that stoichiometric combustion is the most efficient condition for the utilization of thermal energy (Fig. 12) 111/

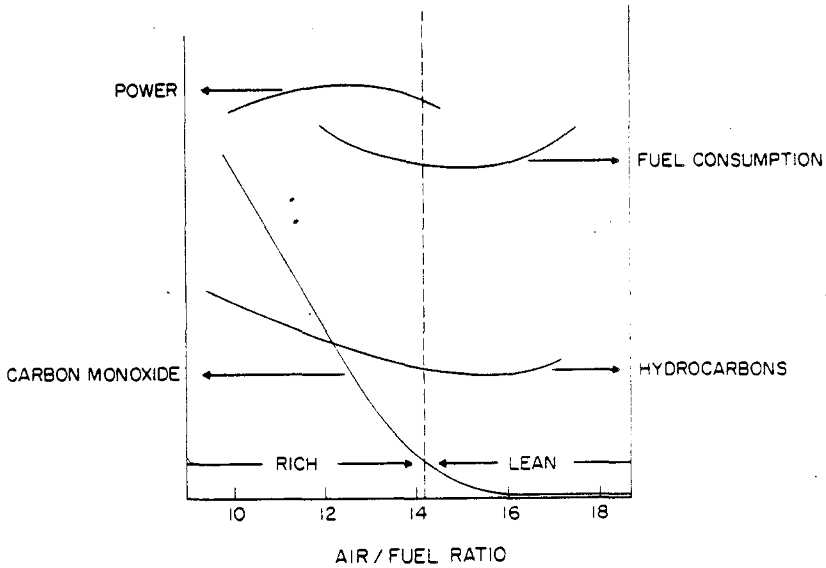

FIGURE 12: Influence of air/fuel ratio on power, fuel consumption and emissions. 112/

110/ Combustion Technology Manual. Industrial Heating Equipment Association: Arlington, Virginia, 1980. p. 9.

111/ Ibid., p. 226.

112/ I.C.H. Robinson. "The Effect of Gasoline Additives on Fuel Economy." In Fuel Economy of the Gasoline Engine: Fuel Lubricant, and other Effects. Ed. by D.R. Blackmore and A. Thomas (Shell Research Ltd.), John Wiley & Sons. New York. 1977. p. 84.

In this ideal situation, the gasoline is fully vaporized and distributed evenly to and within the cylinders, where blue-flame combustion converts the heat energy of the gasoline to mechanical energy. The gasoline must first be vaporized to individual molecules before oxidation to carbon dioxide and water can occur. 113/ As discussed earlier, the incomplete vaporization and uneven distribution greatly affect the air/ fuel ratio in individual cylinders even in the most modern automobile engines. In the rich cylinders, there is insufficient air to burn the relatively large amount of gasoline present, creating most of the HC and CO emissions. In the lean cylinders, the heat and pressure in the primary flame force some of the excess oxygen to combine with the nitrogen in the air rather than oxidizing the hydrogen and carbon for which the oxygen normally has a greater chemical affinity. To reduce NOx emissions, engine manufacturers currently recirculate some of the exhaust gases back into the primary intake air. Because these gases are less reactive, the formation of NOx is inhibited but the combustion process is deprived of oxygen that could be used to produce more energy from the unburned hydrocarbons.

Excess oxygen is not desirable either. Although it can decrease HC and CO emissions within certain limits, it does reduce power because the full amount of the work available from the fuel is reduced by the lower flame temperature resulting from the heating of the excess air to the temperature of the burned gasoline. 114/ The flame tempera-

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113/ Ibid., p. 13.

114/ Combustion Technology Manual, p. 4.

ture can be increased to its maximum, therefore, by using a stoichiometric air/fuel ratio (when possible) and low levels of residuals or recirculated gas. 115/ The flame stability afforded by the use of a vaporized charge is very high under these conditions. 116/

Despite the recent interest in lean-burn combustion systems, it may be more desirable to use an air/fuel mixture that is closer to stoichiometric. If the combustion conditions can be brought closer to the ideal stoichiometry, then the optimum mixture is probably also very close to stoichiometric. In an internal combustion engine, it is impossible to get something for nothing as some lean-burn techniques attempt to do. The best that can be achieved is the conversion of as much chemical energy in the fuel charge as possible into mechanical energy that can perform useful work with a minimum of harmful emissions.

2. Octane Requirements

One of the most unexpected and potentially most important gains shown by the Webster-Heise valve is its lowering of engine octane requirements by ten points or more. To understand the reasons for this reduction,

115/ Manoochehr Rashidi (Univ. of Technology, Theran). "The Nature of Cycle-By-Cycle Variatioent in the S.I. Engine From High-Speed Photographs." Combustion and Flame, Vol. 42. 1981. p. 121.

116/ G.A. Harrow and P.H. Clarke (Shell Research Ltd). "Mixture Strength Control of Engine Power: Fuel Economy and Specific Emissions from Gasoline Engines Running on Fully Vaporized Fuel/Air Mixtures." In Fuel Economy and Emissions of Lean Burn Engines, Institute of Mechanical Engineers, Conference Publication 1979-9, June 12-14, 1979, p. 12.

which was not an original objective of the inventors, it is necessary to examine first the combustion problems identifiable in standard engines and then to analyze the effects that the Webster-Heise valve has on them.

When the fuel charge is burned in a combustion chamber, the gasoline vapor and oxygen (which comprises approximately one-fifth of the air) combine and form new compounds. This reaction releases a large amount of heat which drives temperatures up to about 3500 ^{o}F. This creates pressure on the gases in the cylinder which expand to push on the piston, forcing it downward on its power stroke. Normal combustion consists of three phases: 117/

> As soon as the ignition spark jumps the gap of the spark plug, a small ball of blue flame develops in the gap. This ball is the first stage or nucleus of the flame. It enlarges with relative slowness and, during its growth, there is no measureable pressure created by the heat.
>
> As the nucleus enlarges, it develops into the hatching-out stage. The nucleus is torn apart, so that it sends fingers of flame into the mixture in the combustion chamber. This causes enough heat to give a slight rise in temperature and pressure in the entire air-fuel mixture. Consequently a lag still exists in the attempt to raise pressure in the entire cylinder.
>
> It is during the third stage, or propagation, that the effective burning of the fuel takes place. The flame burns in a front which sweeps across the combustion chamber, burning rapidly and causing great heat with its accompanying rise in pressure. It is this pressure which causes the piston to move downward.
>
> During normal combustion, the burning is progressive. It increases gradually during the first two stages. But, during the third

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117/ Toboldt and Johnson, p. 230.

> stage, the flame is extremely strong as it sweeps through the combustion chamber. However, there is no violent or explosive action such as when detonation (ordinarily responsible for pinging or knocking) occurs.
>
> If detonation takes place, it occurs during the third stage of combustion.

When the flame is first propagated, it sweeps from the area around the spark plug toward the walls of the combustion chamber. Because the air/fuel mixtures used in all production gasoline engines contain a substantial amount of liquid fuel droplets, especially on the wetted surface of the cylinders and the piston heads, fuel-rich pockets (due to incomplete vaporization and poor mixing) tend to develop in the extremities of the combustion chamber. These pockets are compressed and heated far past the self-ignition point (even for high-octane fuels) by the combustion emanating from the spark plug. As the flame front advances, these unburned gases and droplets are further heated and compressed. This extreme heating of the unburned mixture can cause spontaneous ignition and explosion independent of the flame. It is this rapid, uncontrolled burning that is known as detonation and is perceived as "knock" or "pinging" when the rapidly burning flame front, expanding outward from the spark plug, collides with the the secondary wave front produced by the detonation of the fuel-rich pockets ahead of the primary front. 118/

Detonation is more than an annoyance or an indication of inefficient engine operation. It can do great harm to an engine and can considerably impair its performance and expected life. It can shatter pistons, burst

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118/ Toboldt and Johnson, p. 230.

cylinders, crack cylinder heads, melt pistons, overheat engines, break spark plugs, overload bearings, increase fuel consumption, and decrease power. 119/ The problems caused by detonation have been observed by Khovahk: 120/

> An engine should never be allowed to operate for a long time with knocking, since the shock waves sharply increase heat transfer from the combustion products to the walls. This leads to overheating of the engine and destruction of some of the components in the combustion chambers (piston edges, gaskets between the cylinder and its head, electrodes and insulators of spark plugs). The vibrational nature of the load on the piston with detonation may destroy the antrifriction layer in the connecting rod bearings and intensify the wear of the upper part of the cylinder liners, since the shock waves destroy the oil film on the surface of the metal, causing dry friction and also corrosive wear by the active substances, particularly nitrogen oxides, contained in the combustion products.

There are several factors that contribute to detonation. 121/ These include lean air/fuel mixtrues (which are more likely to contain uneven distribution of the gasoline with each cylinder), fuel of too low an octane rating (especially under poor vaporization and mixing conditions), high compression ratios, overadvance of ignition timing, engine lugging, and buildup of carbon deposits in the combustion chamber.

A separate but related problem is preignition, the burning of the fuel charge before the ignition spark. If this premature combustion is completed before the spark-induced ignition begins there is no

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119/ Ibid., p. 231.

120/ M. Khovakh. Motor Vehicle Engines. MIR Publishers: Moscow 1971. p. 142.

121/ Toboldt and Johnson, p. 231.

"knock." Preignition can cause detonation which, in turn, can cause more preignition. The principal cause of preignition is excess heat, particularly that retained by hot carbon deposits which act as impromptu spark plugs. This can raise the octane requirements by several numbers and, if excessive, can break the crankshaft.

The negative effects of detonation and preignition have led gasoline refiners to increase the octane ratings of their fuels. The rating of a fuel is made by comparing it to mixtures of normal heptane and iso-octane (hence the term) in a test engine under certain test conditions. The combination of these pure hydrocarbons which provides the same knocking in the engine as the gasoline being tested is considered to have that "octane." The octane number of the fuel is the percent of the iso-octane in the matching mixture of iso-octane and normal heptane. 122/

The gasoline additive used as the most common knock suppressant for the past 50 years is tetraethyl lead. Other additives are also used to reduce the buildup of carbon deposits, to absorb water in the fuel, and to lubricate the valve stems and upper cylinder walls. Most of these additives have high associated toxicity, and some are being phased out by law. Fuel economy was not a principal objective in the development of these additives. 123/ The major concern was in avoiding engine destruction due to "knock".

Both detonation and preignition are serious combustion problems. Both are uncontrollable explosions which generate their own flame fronts.

122/ Ibid., p. 231.

123/ Robinson, p. 79.

Because they normally occur early in the process of compression and ignition, both violations reduce engine power because work is required to compress the combustion products. 124/ They also transfer additional heat to the cylinder walls because burnt gases with high temperatures remain longer in the cylinders.

Even with the addition of knock suppressants, carbon deposits in high-compression engines using high-octane gasoline sometimes produce foci of self-ignition independent of the primary flame front. Known as "rumble", this violation occurs after periods when the engine has been operating for long periods under light loads (forming carbon deposits in the process) and then run at full throttle. 125/ Often the engine will continue to run at very inefficient levels after the ignition is turned off because the compression and the hot carbon deposits are sufficient to cause self-ignition. This is known as "dieseling" or "engine run-on."

Tetraethyl lead and other anti-knock additives are negative catalysts which slow down the rate of flame travel and combustion so that extreme heat and pressure waves will not be created. This reduces the detonation tendency of the air /fuel charge and lowers the combustibility of the fuel-rich pockets in which detonation takes place.

Reducing the volatility of the fuel (low-octane gasoline is more reactive than high-octane) through the use of negative catalysts hinders detonation beyond the primary flame front. It does, however,

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124/ Khovahk, p. 144.

125/ Ibid., p. 145.

have numerous associated disadvantages. Most anti-knock additives, particularly tetraethyl lead and aromatics, are highly toxic, and some are carcinogenic. Because of this, Federal laws have been enacted to reduce and to eventually phase out their use. At the same time, the demand for fuel economy has led manufacturers to increase compression ratios, which increase the octane rquirements of their engines. At the same time, the refining industry is severely depressed and only the largest companies can afford the expensive reconfigurations necessary to increase octane of their gasolines. Those that can increase them do so at a great expense in extra crude oil consumed through more severe processing.

The alternatives to chemical octane have never been attractive because there appeared to be no effective way to improve the conditions in the combustion chamber. The fuel-rich pockets, carbon deposits, and low-density air inherent in automobile engine strictly limited the options. The Webster-Heise Corporation, however, claims that processing the charge (as described earlier) through a valve eliminates or greatly reduces those factors that artificially increase octane requirements. The highly vaporized and fully mixed charge prevents the formation of fuel-rich pockets, the low-temperature vaporization reduces the charge temperature, and because combustion is more complete, carbon deposits do not form.

The rate of combustion is of critical importance in determining the efficiency of an engine. As Khovahk has observed: 126/

126/ Khovahk, p. 123.

> Combustion takes place in the gaseous phase. For the reactions of oxidation to develop at sufficiently high velocities, the liquid fuel should be vaporized and its vapours mixed with the air. The process of combustion takes place at the maximum velocity in homogeneous mixtures when the fuel molecules are uniformly distributed among the molecules of oxygen. In heterogeneous gas mixtures, the rate of combustion is mainly determined by the velocities of mutual diffusion of the fuel vapours and air, while the rates of the chemical reactions are of a secondary importance. The rate of liquid fuel combustion is limited by the rates with which it evaporates and the vapours formed mix with air.

Because of the conditions that apply in a conventional engine, slowing the reaction rate of the fuel in the pockets ahead of the flame front is the only way that detonation can be avoided when it would otherwise occur. If those conditions are made more benign, as is possible through improved charge preparation and distribution, then a fuel of substantially lower octane can be used without detonation. Khovahk has noted that "detonation is hampered by the factors that accelerate combustion of the last portion of the charge in the flame front." 127/ If the flame travel is faster and less time is required to develop the preflame reactions in the unburned part of the charge, then the tendency to detonate is reduced. 128/ If the air/fuel mixture, therefore, is highly vaporized and homogeneous, is relatively low in temperature (but above the dew-point temperature), and is highly turbulent (to accelerate the propagation of the flame front), then fuel with higher reactivity (lower octane) can be used. The size of the octane reduction varies but, based on laboratory

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127/ Ibid., p. 143.

128/ Ibid., p. 147.

tests, appears to be at least 10 octane points lower and may be as much as 15.

Flame speed is known to increase with decreasing initial droplet size, with the fastest speed for vapor. 129/ The presence of droplets produces local variations in the air/fuel mixture which can cause the formation of a secondary diffusion flame in the wake of the propagating flame and produce local variations in the combustion temperature. This unsteadiness is due to the time-varying stratification of the droplets and their transient heating. 130/ These variations work against efficient engine operations and tend to increase the formation of undesirable emissions. In a premixed homogeneous charge, the secondary flame does not develop and the primary flame tends to propagate with a steady velocity. 131/

The ability of the Webster-Heise system to run on low octane gasolines with high spark advances and without detonation (as shown in the Summary of Tests) tend to suggest that vaporization of the gasoline is responsible for the likely absence of a secondary flame and consequent "knock."

129/ B. Seth (Princeton Univ.), S.K. Aggarwal (Carnegie-Mellon Univ.), and W.A. Sirigano (Carnegie-Mellon Univ.). "Flame Propagation Through an Air-Fuel Spray Mixture with Droplet Vaporization." Combustion and Flame. Vol. 39. 1980. p. 149.

130/ Ibid., p. 165.

131/ Ibid., p. 164.

Another apparent factor in reducing the octane requirement with a Webster-Heise valve is the increased turbulence of combustion. It can be inferred from internal combustion theory that, because of the homogeneity of the charge, the intensity of the turbulence of the charge upon admission to the cylinder is probably higher than in a standard engine. This turbulence greatly increases the velocity of the flame front. 132/ Experiments independent of the Webster-Heise development have shown that these intensive vortices and turbulent pulsations distort the flame front and break it into separately burning foci which greatly increase the actual surface of combustion by several orders of magnitude. 133/ The turbulent pulsations that are smaller than the thickness of the laminar flame front do not produce distortions, but they do intensify the processes of heat transfer and diffusion in the flame front thereby increasing the combustion rate in the foci. These two factors combine to cause the velocity of the turbulent flame to increase in approximate proportion to the intensity of the turbulence. 134/ These factors may also apply in the Webster-Heise system.

Another important factor in octane requirements is the manner in which the charge burns. As Khovahk has shown: 135/

> Heterogeneous mixtures such as jets of gas flowing into air or droplets of atomized liquid fuel suspended in air burn in a quite different manner than homogeneous

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132/ Khovahk, p. 131.

133/ Ibid., p. 131.

134/ Ibid., p. 131.

135/ Khovahk, p. 132.

> ones. The rate of combustion of a heterogeneous gas mixture is determined in practice by the velocity of diffusive mixing of the fuel with the oxidant, since the chemical reactions of combustion have much higher rates than the mixing processes. This kind of burning is therefore known as diffusive combustion.
>
> The rate of combustion of liquid fuel droplets is mainly determined by the rate of vaporization (the vapours of fuel formed on the droplet surface diffuse into the air surrounding the droplet and form a combustible mixture at some distance from it.

The heterogeneous mixtures always develop fuel-rich local zones which serve as centers for ignition of the surrounding leaner mixture. This permits the use of a very lean mixture but greatly increases the potential for harmful detonation and NOx formation.

In a series of tests at the Environmental Testing Corporation in Denver, Colorado (an EPA-recognized testing laboratory), use of the Webster-Heise valve was shown to reduce the octane requirements of the test car (a 1979 Chevrolet Monte Carlo) by 10 or more points (see Summary of Tests).

In real terms, the octane gains are greater than indicated because they were not offset by negative effects in other areas. Results in all other categories were favorable (low emissions, high torque, high fuel economy, and good driveability). The ability to use 75-octane fuel with no offsetting losses could eliminate the need to boost the octane of gasoline, a practice that is expensive in terms of crude oil requirements, of cost to the end-user, and of deterioration of air quality. The lowest octane fuel that can legally be sold is 85 (available only a high-altitude locations). The test data shows that the Webster-Heise valve permits improved performance on fuel 10 octane points lower than that on the card tested so far; wider applicability will need to be determined by testing on a wide range of vehicles.

As a practical matter, refiners probably would not wish to push octanes as low as 75 but would probably prefer to sell the gasoline (once a large enough fleet were established) directly as it comes from the fractionating towers. The octane of this raw gasoline is normally about 82 or 83 (R+M/2), and it would need no further octane enhancement. It is the current effort to boost octane from these levels to the upper 80's and low 90's that consumes so much crude oil, and that adds significantly to the cost of the gasoline at the pump (as much as 20 cents per gallon).

The octane reduction observed in the test of the Webster-Heise valve has also been observed independently in other tests. In its work on fast-burn engines, the General Motors Research Laboratories compared the octane requirements of a fast-burn engine and a slow-burn engine. 136/

> Comparing these two chambers shows that the fast burn chamber requires a fuel octane number of only 80 to operate at MBT (minimum advance for best torque). In contrast, the slow-burn chamber needs a fuel with a 97.5 octane rating for optimum timing. Alternatively, retarding spark timing to allow an 80 octane number fuel to be used in the slow-burn chamber would reduce efficiency significantly.
>
> A diagnostic study of combustion in the two chambers identified shorter combustion time in the fast-burn chamber as the dominant factor contributing to its lower octane needs. Specifically, analysis of pressure movement in both chambers showed end-gas temperature and pressure to reach higher values in the fast-burn case, primarily due to its higher energy release rate. Despite this higher temperature, more rapid flame front propagation into the end gas more than compensates.

136/ James N. Mattavi (General Motors Research Laboratories). "Fast-Burn Chamber Design Improves Efficiency, Lowers Emissions." Automotive Engineering, November 1980. p. 90. Based on the same author's SAE Paper 800920 (SP-467), "The Attributes of Fast-Burning Rates in Engines."

Mattavi observed that fast-burning of the charge is a fundamental approach for reducing octane requirements. Most of the industry efforts, such as the May "Fireball" concept, have been concentrated on new combustion chamber designs that increase the swirl to reduce the opportunity for detonation pockets to form. All of these systems introduce liquid rather than vaporized gasoline into the chamber. None of them have yet to be used in large-scale production. The Webster-Heise valve may prove to be a far less expensive and possibly more efficient means of accomplishing the same objectives as the fast-burn chambers: reducing octane requirements, improving fuel economy, and lowering emissions of pollutants.

3. Torque

The conditions for maximum efficiency in an automobile engine were established in Paris in 1862 by the originator of the operating cycle theory for the internal combustion engine, Alphonse Beau de Rochas. He determined that the engine should have the following characteristcs: 137/

(1) maximum cylinder volume with a minimum cooling surface,

(2) maximum rapidity of expansion,

(3) maximum ratio of expansion, and

(4) maximum pressure of the ignited charge.

The two conditions that are of primary interest here are (2) and (4). Tests to date suggest the likelihood that the Webster-Heise valve,

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137/ Encyclopedia Britannica. Encyclopedia Britannica, Inc.: Chicago, Vol. 12. 1972. p. 389.

conditions of the charge so that combustion can much more quickly (once ignited by the spark) than it can in a conventional engine. Because it reduces the octane requirements of the engine (as indicated by its ability to run on low octane fuels with high spark advance and without detonation, it can use lower-octane fuels which burn faster than those with additives such as lead. Because of the faster burn, the expansion of the combustion products is more rapid and exerts more force on the pistons. The high density of the intake charge also increases the available torque because there is a greater mass to expand upon combustion.

Obtaining the maximum pressure of the ignited charge is crucial to achieving the maximum operating efficiency. The maximum work of a cycle and the maximum power and efficiency of an engine can be obtained when the main combustion phase begins and ends almost symetrically with respect to top-dead-center (actually about 10^{o} after top-dead-center to get leverage on the crank). Because standard engines are not octane tolerant below certain limits, either the octane must be increased or the timing retarded. If the octane is increased, the combustion starts late and takes place over a range of 30 to 40 crank angle degrees. During that time, the volume of the combustion chamber increases as the piston moves downward on its power stroke. The effective compression ratio during most of the combustion, therefore, is lower than it is at top-dead-center (TDC). If the timing is retarded (to decrease the pressure on the detonation-prone fuel-rich pockets ahead of the flame front) then the expansion of the gases does not occur until after the volume of the combustion chamber begins to increase as the piston moves away from it.

In both cases, the engine is not operating with maximum efficiency because the maximum available pressure is not being exerted due either to the slow reaction rate or to the late expansion. This is the principal reason that most modern automobile engines have relatively low torque, especially at low engine speeds. At the very beginning of the development of the four-cycle engine, Beau de Rochas theorized that maximum efficiency could be achieved only if the maximum pressure were exerted just after TDC, followed by expansion during the power stroke. Because the Webster-Heise valve permits combustion to occur rapidly without detonation, the timing can be advanced to provide the maximum pressure at a point just past TDC, thus increasing both torque and fuel economy.

The faster heat release and the greater volumetric efficiency made possible through the use of the Webster-Heise valve means that the peak pressures can be higher and can be made to occur at the moment they will be most effective (just after TDC). As a result, the torque has been shown to be as much as 40 percent higher than standard on 75 octane gasoline, as measured in tests at the Environmental Testing Corporation (see Test 6, Summary of Tests). This was accomplished with better fuel economy (lower brake-specific fuel consumption) than the standard production system.

A gain of that size over standard is substantial, but even more remarkable is that the torque increase began at low RPM. In the Ford tests the torque gain was largest at low engine speeds (1200 RPM) and was maintained throughout most of the test (through 3500 RPM). The difference was greatest at low RPMs, however, where torque is needed most.

As Toboldt and Johnson have noted: 138/

> In the case of the automotive engine, torque is low at low engine speeds and increases rapidly with the speed. Automotive engineers make every effort to increase the torque at low speeds and to remain as nearly constant as possible.

In addition, the Webster-Heise valve apparently eliminates the problem of "manifold lag." Burtner and Morris have described this phenomenon: 139/

> It is well known that octane distribution over the gasoline boiling range affects road octane numbers of loaded gasolines in manual transmission cars. At full-throttle and low engine speed, some of the unvaporized gasoline flows along the walls of the intake manifold so that at the beginning of an acceleration, the cylinders are receiving more than the normal share of low-boiling components. Because of this phenomenon, known as "manifold lag," such cars respond to octane quality in the low-boiling "front end" of the gasoline.
>
> The higher boiling aromatics tend to remain in the "heavy end" of the gasoline and therefore do not contribute to octane quality of the "front end" while increasing the octane number of the whole gasoline.

These octane distribution effects can be important in limiting early torque. In conventional engines the components with the greatest heat content (and the highest boiling points) are the least likely to reach the cylinders as burnable vapor when additional torque is needed. As a result, only the lightest, most volatile components are burned, and these are the ones are the most likely to cause detonation. Because their heat

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138/ Toboldt and Johnson, p. 94.

139/ R.E. Burtner (Sun Group) and W.E. Morris (E.I. du Pont de Nemours Inc.). "The Effects of Refinery Gasoline Components on Road Octane Quality." Paper 780949, Society of Automotive Engineers, 1979, p. 3523-3524.

content is low they cannot generate as much pressure as a charge with the full range of gasoline components, particularly the heavy ones which are less volatile but which contain most of the heat energy. 140/

4. Cycle-By-Cycle Combustion Variations

Cycle-by-cycle combustion variations (CBC) have always been a problem in four-cycle engines, but the problem has become even more vexing with the advent of emission controls. CBC occurs under all operating conditions and increases as the air/fuel ratio moves away from a stoichiometric value in either a lean or very rich direction. 141/ It occurs to the greatest degree when excessive amounts of exhaust gases are recirculated to reduce the oxygen available for NOx formation. 142/ As exhaust gas recirculation (EGR) increases, the combustion rate slows and the flame stability deteriorates. If CBC variations are too extreme, partial burn occurs and the unburned charge is carried over to the next cycle as a residual gas. Consequently, unburned HC and fuel consumption skyrocket. CBC variation is the random variation in the time between the spark and the establishment of a stable flame front in successive firings. 143/

140/ Toboldt and Johnson, p. 229.

141/ Rashidi, p. 111.

142/ H. Kuroda, Y. Nakajima, K. Sugihara, Y. Takagi, and S. Muranaka (Nissan Motor Co.). "The Fast Burn with Heavy EGR, New Approach for Low NOx and Improved Fuel Economy." Paper 78006, Society of Automotive Engineers, 1979, p. 5-7.

143/ Rashidi, p. 112.

In an engine running at 2500 RPM and having a typical spark duration of a 20° crank angle, the limiting effect of CBC variations is the equivalent of randomly retarding timing between 0° and 20°. 144/ This causes considerable variations in the rate of pressure rise and peak cylinder pressure and greatly reduces efficiency. This degradation of the combustion process limits the maximum air/fuel ratio (currently used to reduce emissions and to lower fuel consumption).

Traditionally, the method used for reducing CBC variations was to operate the engine with a richer mixture but, because of restrictions on exhaust emissions and the need for better fuel economy, this method is no longer practical. The ideal approach is to consistently increase the average combustion rate, as they Webster-Heise valve appears to do. This was not done by the auto industry, however, because faster combustion promoted detonation of the incompletely vaporized and poorly mixed charge. The effect of the fast-burn on CBC variations has been described by Rashidi: 145/

> Reducing the delay period in the second phase of ignition or reducing the flame stabilization time decreases the cyclic variation. This can be achieved by selecting a mixture with a high reaction rate. In this respect the high temperature of the flame nucleus is important.

With a fast burn, combustion duration declines sharply. With 20-percent EGR, the combustion duration of fast burn is virtually the same as that of a conventional engine with no EGR. An improvement in the quality and rate of combustion, therefore, can greatly decrease the

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144/ Rashidi, p. 120.

145/ Rashidi, p. 121.

CBC variations in cylinder pressure. 146/ The shorter combustion duration also reduces pumping losses (the piston does not have to compress the burning charge as much as the crank approaches TDC) which substantially reduces fuel consumption and lowers NOx emissions. The Webster-Heise valve's inventors claim that because it conditions the charge to accept fast-burn rates and reduces the need for EGR, it is very effective at improving combustion stability and eliminating CBC variations.

5. Fuel Economy

The thermal efficiency of conventional gasoline-powered engines is very low. Because of the high internal friction in four-cycle engines, the theoretical maximum is only about 25 percent conversion of the thermal energy mechanical energy. 147/ Virtually no engines achieve these levels because of incomplete combustion, poor mixture distribution, detonation, pumping losses, engine deposits, and other inherent problems. A relatively new car (after break-in) might get as much as 13 percent, but about 10 percent is more typical as wear and deposits accumulate. 148/ In an engine far out of tune or badly worn, the efficiency can drop to as low as 6 percent or less.

The Webster-Heise valve appears to increase the thermal efficiency of the engine in several ways. The better mixture preparation and equal

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146/ H. Kuroda, Y. Nakajima, K. Sugihara, Y. Takagi, and S. Muranaka (Nissan Motor Co.). "The Fast Burn with Heavy EGR, New Approach for Low NOx and Improved Fuel Economy." Paper 780006, Society of Automotive Engineers, 1979, p. 7.

147/ Robert L. Loftness. Energy Handbook. Van Nostrand Reinhold Co.: New York, 1978, p. 409.

148/ Harrow, p. 103.

distribution result in more complete combustion and more effective work on the crankshaft. The vaporized state of the fuel and the cooler air temperature reduce detonation (which lowers fuel economy) and improves torque (less fuel is consumed to do the same amount of work). The Webster-Heise valve apparently facilitates the greater use of the heavy components of gasoline which contain most of the energy (Fig. 5). When this fuel is burned, much of which would otherwise be lost as part of the exhaust in the form of unburned or partially oxidized hydrocarbons, it provides additional energy that reduces overall fuel requirements. This is consistent with experiments which have shown that a simultaneous reduction in droplet evaporation and entrainment reduces the combustion efficiency. 149/

Perhaps the most important factor, however, is the increased rate of combustion (fast-burn) which has been shown to improve fuel efficiency by about 10 percent compared to conventional engines under equal NOx conditions. 150/ Fast burn greatly reduces the cycle heat rejection, which has a direct and significantly effect on fuel consumption. The energy within the charge that is transferred to the coolant during the compression, combustion, and expansion phases of the engine cycle when the valves are closed is particularly important because it represents

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149/ Y. El. Banhawy and J.H. Whitelaw (Department of Mechanical Engineering, Imperial College of Science and Technology). "Experimental Study of the Interaction Between a Fuel Spray and Surrounding Combustion Air," Combustion and Flame, 1981, Vol. 42, p. 274.

150/ Masanori Harada, Tadashi Kadota, and Yashitaka Sugiyama (Nissan Motor Co.). "Fast-Burn Engine Developed." Automotive Engineering, February 1981. p. 43.

a direct depletion of the energy available for useful work. 151/ The heat losses and related effects reduce the thermal efficiency of a standard engine by about 40 percent. 152/ If greater use is made of the chemical energy available in the gasoline, as it is claimed to be in Webster-Heise modified engines, then the overall engine efficiency and fuel economy are also increased. The application of this principle, plus the factors already noted, allow the modified engine to operate at a level much closer to the theoretical maximum efficiency.

The high heat losses in conventional engines not only increase fuel consumption directly but also indirectly through increased detonation. This necessitates retardation of the combustion timing to maintain the optimal pressure-versus-crank angle history in each cylinder. 153/ The elimination of cycle heat losses would increase fuel economy by about 12 percent in most engines, and advancing the timing (where possible) would add another one percent for each angle of advance. 154/ Webster-Heise claims that the valve greatly reduces, but does not completely eliminate, these heat losses. This probably accounts, however, for at least some of the fuel economy gains observed in all of the tests.

151/ J.M. Novak and P.N. Blumberg (Ford Motor Co.). "Parametric Simulation of Significant Design and Operating Alternatives Affecting the Fuel Economy and Emissions of Spark-Ignited Engines." Report 780943, Society of Automotive Engineers.

152/ Marks, p. 9-108.

153/ Novak and Blumberg, p. 3488.

154/ Ibid., p. 3491.

As Novak and Blumberg point out: 155/

> The high wall and charge temperatures associated with reduced heat losses would undoubtedly aggravate the already serious problem of engine knock. Hence, any design alternative that reduces in-cylinder heat losses without addressing the knock limitation would be impractical.

They also observed that to prevent deterioration of the combustion process, especially with charge dilution, "would require major advances in fuel preparation, ignition, and controlled turbulence for its implementation." 156/

In EPA-recognized laboratory tests, the Webster-Heise valve has shown substantial gains in fuel economy. In the EPA cold-start test and using an early prototype valve, the Webster-Heise modified automobile showed a 9.2 percent increase in fuel economy (with lower emissions) over baseline. The gains in other official tests were somewhat higher, ranging up to 20 percent in some. In unofficial road tests and under favorable conditions, even greater gains on the highway have been observed.

It is particularly important to note that in the EPA highway economy tests on October 15, 1980, the Webster-Heise car (1979 Monte Carlo) achieved 25.9 miles per gallon (mpg) with 75 octane fuel and a timing advance of 13^{o} before TDC (See Summary of Tests). The same car, without the valve, would barely run on that fuel at that timing and had severe "knock." Even with 97 indolene (a high-octane research gasoline) and the same spark advance, the fuel economy of the baseline car was only 23.8 mpg,

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155/ Novak and Blumberg. p. 3493.

156/ Ibid., p. 3497.

8.1 percent lower. In the July 1982 tests at ETC on a 1982 Oldsmobile Cutlass Supreme, (See Test 6, Summary of Tests), the fuel economy on 75 octane gasoline was 35.614 MPG versus 31.414 MPG for the same car without the valve on 97 octane, an increase of 13.4 percent. The EPA highway fuel economy for that model is 30 MPG.

As a general rule, each one degree of spark retardation causes a one-percent reduction in fuel economy. 157/ For this reason, the actual fuel economy obtained with the Webster-Heise valve tends to be greater than baseline because of the additional timing advance made possible by the lower octane requirments of the modified engine. The fuel economy of most new cars is less than the EPA numbers would suggest because the timing has to be retarded in order to prevent detonation when using 87-octane gasoline (EPA tests are run on 97-octane gasoline). This reduction in fuel economy can be as much as eight percent, but spark retardation is widely practiced by new car dealers to eliminate "knock" when their customers complain about it in their engines. 158/

The greatest potential for fuel savings is probably at low RPMs in urban stop-and-go driving (Fig. 13). Tests indicate that the greatest fuel economy improvement (possibly as much as 30 percent) could be expected in that type of driving because it is the mode in which combustion in conventional engines is the least efficient. As Knovakh has reported. 159/

157/ U.S. House of Representatives Committee on Government Operations. Automobile Fuel Economy: EPA's Performance. U.S. Government Printing Office: Washington, D.C. May 13, 1980. p. 11.

158/ U.S. House of Representatives Committee on Government Operations, p. 11.

159/ Khovakh, p. 139.

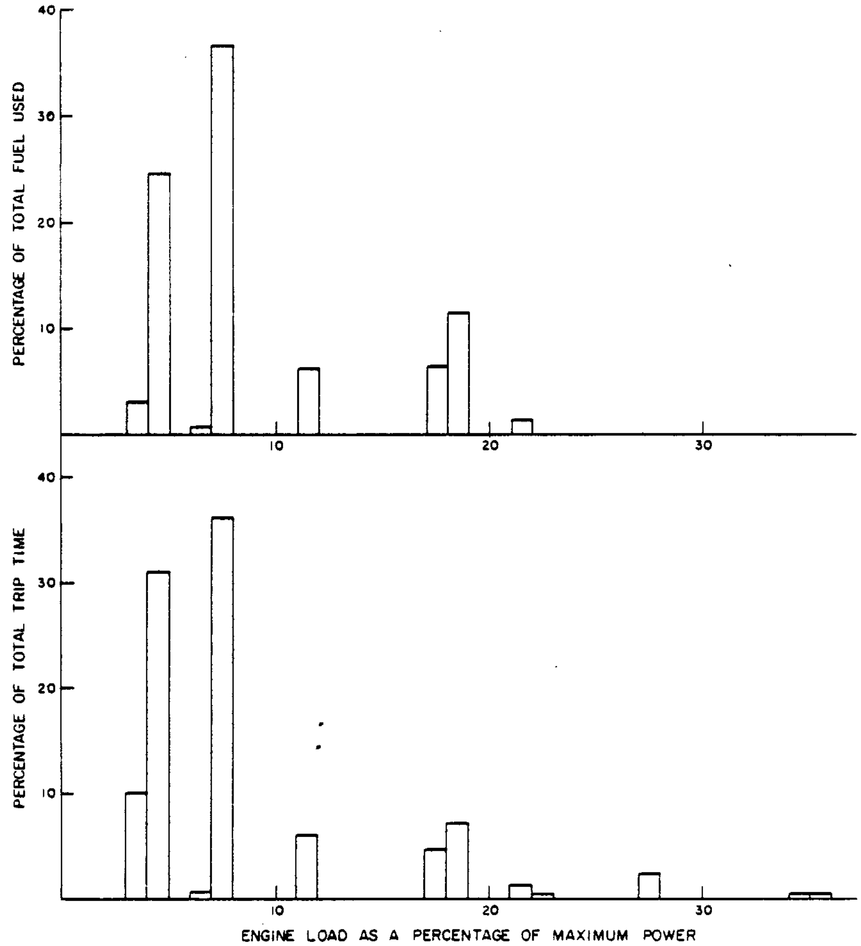

Figure 13. Engine and Fuel utilization patterns found for typical road service (1.8 l passenger car) 160/

160/ Harrow, p. 101.

> When the power of an engine is reduced by throttling, the initial and final compression pressures decrease and the dilution of the working mixture with the residual gases increases. First of all, this appreciably impairs ignition of the mixture by a spark and the development of the initial focus of combustion. This prolongs the initial phase, the process of combustion loses its stability and frequently cannot be resumed in some cycles.
>
> This difficulty can be overcome to a certain extent by so enriching the mixture with considerable throttling as to make spark ignition more dependable (less than 0.8-0.9). But here too, it is very difficult to avoid combustion continuing during a substantial portion of the expansion stroke, since it is impossible to ensure uninterrupted ignition at large advance angles when the compression pressures are still very low.
>
> Poor combustion at low loads and the necessity for mixture enrichment are among the principal shortcomings of spark-ignition petrol engines which cause a waste of fuel and the ejection of a large amount of the products of incomplete combustion (including carbon monoxide and other poisonous substances) into the atmosphere together with the exhaust gases.

There are two principal reasons for the low combustion efficiency of conventional engines at low engine speeds. The first is the longer time available during each cycle for combustion to occur. When it does take place, it develops unevenly and produce limited torque. The second is the highly restricted volume of air that manages to get by the throttle plate (it is nearly a total restriction when closed at idle). In unmodified engines, the limited air flow at low engine speeds is even less effective than usual in atmozing and partially vaporizing the gasoline. As a result, the standard engine has difficulty idling at speeds below 500 RPM. The Webster-Heise valve, on the other hand, is claimed to maintain a high degree of turbulence, even with heavy throttling, because the fuel is still substantially vaporized rather than atomized in large droplets. This permits a faster combustion rate, even at low engine speeds. Webster-Heise reports that in its test the valve allowed engine speeds as low as 300 RPM without significant deterioration of combustion quality. This means not only that less fuel will be used at complete idle but also that far fewer engine deposits (particularly carbon), which could impair performance later, are likely to form.

This aspect takes on added significance when considered in the context of the EPA tests. The EPA certification test consists of 55 percent city driving and 45 percent highway driving. According to the Department of Transportation, however, these percentages are not representative of actual driving patterns. DOT reports that 90 percent of the driving is done in city and rush-hour driving and only 10 percent is done at high speeds on hghways. 161/ That 90-percent is where most of the improvement in fuel economy can come because it is the least fuel-efficient mode of driving.

This weighting of the EPA tests inflates the fuel economy numbers to the high side and consequently they are seldom matched in actual experience. One of the main reasons that new car buyers do not obtain the fuel economy promised in the automakers' advertisements is that

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161/ Federal Highway Administration. Department of Transportation. Purposes of Vehicle Trips and Travel. U.S. Government Printing Office. Washington, D.C. December 1980. p. 10.

the stop-and-go mode of rush-hour driving (over 35 percent of all driving) is far more important than its representation in the tests. Because this is also the most efficient engine speed at which to operate, the potential gains over standard is much greater than in other modes of driving.

C. POST-COMBUSTION EFFECTS

1. Emissions

The presence of harmful emissions in the exhaust of internal combustion engines has been a source of concern for over two decades. Limited progress has been made in reducing them, but a substantial air quality problem still remains, particularly in urban areas. The efforts of the automobile industry have been directed at devices such as the catalytic converter (which is sensitive to contamination). Efforts to reduce NOx often result in increases in HC and vice versa. The Webster-Heise valve is unusual in that it apparently reduces all three pollutants simultaneously (especially if the manifold is cooled), although not all are reduced to the same extent.

HC emissions, as indicated earlier, are principally the result of incomplete combustion. This is especially true if the engine is run rich (air/fuel ratio less than 14.7:1). Enrichment assures maximum power and stable operation at low loads and idle. The lack of oxygen, however, prevents complete combustion of all of the charge and reduces the evolution of heat upon combustion. 162/ As a result, the products of incomplete combustion (CO, free hydrogen, CH4, and others) appear.

A direct relationship exists between "knock" and HC emissions. For this reason, the reactions that take place ahead of the flame and those that occur behind it are most important. As Bracco observes, "the pre-flame reactions are responsible for the process of engine knock and

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162/ Khovahk, p. 56.

determine the nature of the unburned hydrocarbons that are emitted when the flame fails to process all of the combustible mixture ahead of it." 163/

A major reason for the high concentrations of liquid gasoline in the extremities of the cylinders, which lead to detonation and contribute to high emissions, is the admission of the gasoline to the cylinders in the form of liquid droplets. These droplets, especially the largest ones, tend to collect on the metal surfaces of the cylinders, the cylinder heads, and the pistons. This wetted surface is very difficult to ignite properly because of its thickness and because oxygen can reach it from only one side. Because of this surface wetting, the fuel concentrations in the extremities of the cylinders can be quite high even in very lean air/fuel mixtures. When the heat and pressure from the advancing flame front emanating from the spark reaches these areas, the fuel-rich pockets detonate before the flame itself actually reaches them. The Webster-Heise valve, because it apparently delivers a basically homogeneous vaporized charge to the cylinders, greatly limits the potential for the formation of these knock-inducing concentrations.

An effect known as "wall quenching" is also a factor in HC emissions. 164/ This refers to the fact that the temperatures of the metal surfaces of the combustion chamber are lower than that of

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163/ F.V. Bracco (Princeton Univ.). "Combustion and Chemical Kinetics Problems in Internal Combustion Engines." In Progress in Astronautics and Aeronautics, Vol. 62. American Institute of Aeronautics and Astronautics: Princeton, New Jersey. 1977. p. 172.

164/ Andrew A. Adamczyk and George A. Lavoie (Ford Motor Co.). "Laminar Head-On Flame Quenching--A Theoretical Study." Report 780969. Society of Automotive Engineers. 1979. p. 3661.

the combustion itself and tend to extinguish the flame when it reaches them. This normally results in some fuel not being completely burned and in its exhaustion as a pollutant. If quenching occurs early in a cycle, fewer HC molecules are retained by the wall than if it occurs late in the cycle due to the longer post-oxidation time available. 165/ The greater timing advances that have been recorded with the Webster-Heise valve and low-octane gasoline tend to minimize the wall-quenching effect to the extent that it occurs, according to Webster-Heise. Because the charge is apparently vaporized, however, wall quenching is a relatively unlikely source of exhaust HC, in contrast to standard engines which receive heterogeneous charges that are more prone to this effect. 166/ Higher cylinder pressures, such as those produced in the Webster-Heise modified engines, also reduce the quench distance. 167/

In the EPA-recognized laboratory tests, the Webster-Heise modified car obtained HC levels that were as much as 13.4 percent lower than standard (Test 6, Summary of Tests). This pollutant was reduced the least of those tested. It should be noted, however, that the baseline engine had been thoroughly cleaned prior to testing. Therefore, there were no carbon deposits present which probably would have

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165/ Ibid., p. 3665.

166/ R.J. Blint and J.H. Bechtel (General Motors Research Laboratories). "One-Wall Quenching: An Unlikely Exhaust HC Source." Automotive Engineering, April 1982, p. 61 (based on SAE Paper 820063 "Hydro-Combustion Near a Cooled Wall.").

167/ Charles K. Westbrook (Lawrence Livermore Laboratory), Andrew A. Adamczyk and George A. Lavoie (Ford Motor Co.). "A Numerical Study of Laminar Flame Wall Quenching." Combustion and Flame, Vol. 40, 1981. p. 93.

increased the HC levels in the standard engine under normal operating conditions. Conversely, the Webster-Heise test car reportedly did not form carbon deposits even after 80,000 miles, including severe dynometer tests (See Summary of Tests, Informal Testing). If this proves to be characteristic in general use, the difference in HC levels could be expected to increase over time in favor of the Webster-Heise modification.

Carbon monoxide (CO) emissions are subject to many of the same influences as HC, and they tend to rise and fall inversely, although at somewhat different levels. Retarding the spark increases CO emissions because the air flow must increase to maintain power; advancing the spark lowers CO levels. 168/ CO is a measure of incomplete combustion and is indicative of low droplet vaporization rates within the cylinder, assuming a constant air/fuel ratio. It is also one of the most difficult emissions to control in modern catalytic converters. 169/ If the turbulence of the charge is increased, as it is believed to be in the Webster-Heise system, then the oxygen concentration will be sufficiently high for the chemical reaction to proceed with a high intensity. 170/ The CO is then oxidized to CO2 to a greater degree than in a standard engine. In the ETC tests (Tests 3 and 6), the Webster-Heise modification lowered CO by 19.4 percent in the Monte Carlo and

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168/ Craig Marks and George Niepoth (General Motors Corp.). "Car Design for Economy and Emissions." SAE Report 750954 in Automotive Fuel Economy, Society of Automotive Engineers: Warrendale, PA. 1976. p. 159

169/ El Bahnawy and Whitelaw, p. 271-272.

170/ Ibid., p. 270-271.

15.4 percent in the Oldsmobile Cutlass Supreme, although in one test the decrease was 54 percent.

Another difficult emission to control is nitrogen oxide (NOx), which (together with oxidants, hydrocarbons, and sunlight) is responsible for "smog." Because NOx rises when HC is lowered, virtually all emission controls on standard engines are compromises. Because NOx peaks on the lean side of stoichiometric (about 16:1 air/fuel ratio), it has proven to be a barrier to improved fuel economy. 171/

The automobile industry has dealt with the problem of NOx by lowering the spark advance and by using exhaust gas recirculation (EGR) and most recently three-way catalytic converters. A metered amount of exhaust gas is recirculated into the air/fuel mixture on the intake stroke. Because these exhaust gases are deficient in oxygen, they slow down the combustion and absorb heat. 172/ This retarded combustion and shortage of oxygen then reduce temperatures and pressures which, in turn, reduce NOx emissions. Unfortunately, these reductions also increase the HC and CO levels because less oxygen is available for their oxidation and for flame propagation. This can cause misfiring or inhibition of flame development, increase of cycle-by-cycle variations in combustion,

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171/ Novak and Blumberg, p. 3496.

172/ Automotive Encyclopedia, p. 330.

deterioration of driveability, increase in HC and CO emissions, and other disadvantages. 173/

The combustion rate is a very important factor in reducing NOx. As Thring has observed: 174/

> For given engine operating conditions, there is an optimum rate of combustion for minimum NOx emissions from spark ignited engines. In essence, this is because if the combustion rate is too slow, there is plenty of time for NOx formation, while if it is too fast, charge temperature becomes very high and more NOx is formed. It was considered that rates of combustion higher than those attained in current production spark ignition engines might be desirable, firstly because current rates of combustion were believed to be slower than the optimum for minimum NOx emissions and secondly because previous research had indicated that fast burn improved the lean mixture and EGR tolerances. Also, there were indications that fast burn improved economy.

In conventional engines, a shorter burn time would increase NOx emissions. Most of the total NOx comes from the first part of the charge to be burned, due to its continued heating by the combustion of the rest of the charge. 175/ High turbulence combined with a homogeneous vaporized charge, however, should theoretically provide better distribution within the cylinder and should increase the opportunities

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173/ T. Wakisaka, Y. Hamamoto, and S. Ohigashi (Kyoto Univ.) and M. Hashimoto (Kobe Univ.). "Measurements of Air Swirl and Its Turbulence Characteristics in the Cylinder of an Internal Combustion Engine." In Fuel Economy and Emission of Lean Burn Engines, Institute of Mechanical Engineers Conference Publication 1979-9, June 12-14, 1979, p. 51.

174/ R.H. Thring (Ricardo Consulting Engineers Ltd.). "The Effects of Varying Combustion Rate in Spark Ignited Engines." SAE Paper 790387 in Automotive Fuel Economy Part 2, Society of Automotive Engineers: Warrendale, PA. 1979. O. 229.

175/ Ibid., p. 233.

for the oxygen to combine with the hydrogen and carbon in preference to the nitrogen. Combined with the faster flame travel, this tends to reduce the time-temperature histories of each element of the gas in the charge. 176/ The faster combustion reduces the time during which the heating takes place and during which NOx can form. Because the temperatures are most intense in the primary flame, NOx can be greatly reduced by accelerating the combustion rate and by lowering the charge temperature. The addition of a slight amount of EGR to the chamber permits the highest efficiency possible while lowering NOx levels. 177/

The Webster-Heise valve has a greater effect on NOx than on any of the other automobile emissions. The test car showed a 48.6 percent reduction in NOx over baseline on the Monte Carlo (cold manifold) and 45 percent on the Oldsmobile Cutlass Supreme (hot manifold) (Tests 3 and 6, Summary of Tests). Most importantly, these NOx reductions were achieved despite a large increase in the spark advance. The NOx is reduction probably due to two factors: (1) the faster combustion rate and (2) the shorter spray flame. Mellor has shown that faster evaporation leads to a shorter spray flame and results in less NOx production. 178/ The faster vaporization observed by Mellor was achieved

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176/ Ibid., p. 233.

177/ Mattavi, p. 86.

178/ A.M. Mellor (The Combustion Laboratory, School of Mechanical Engineering, Purdue University). "Spray Combustion from an Air-Assist Nozzle. "Combustion Science and Technology, Vol. 9. 1974. p. 165-168.

by increasing the pressure drop through air-assist and pressure atomizing injectors.

2. Driveability

Driveability is a subjective consideration not amenable to quantification. There are, however, several qualitative observations that can be made. As would be expected in an essentially vaporized charge, the cold-start characteristics of an engine are greatly improved with the use of the Webster-Heise valve. Because the automobile uses a weak choke to obtain satisfactory HC emission levels in the cold-start tests, most new cars are very difficult to start when cold (the low vaporization rate of the gasoline is not sufficiently offset by fuel enrichment because it would increase HC emissions). As a result, the standard engine is provided with a choke to restrict the amount of air going into the cold engine so that the small amount of fuel that does evaporate will comprise a large enough part of the total air/fuel mixture to allow combustion to occur.

Harrow has pointed out that all of the mixture problems normally present in a fully warmed-up engine are exaggerated during a cold start for the following reasons: 179/

(1) The manifold has to handle relatively large amounts of liquid.

(2) Because of the low engine speed, the gas velocities through the carburetor are low so that mixing is even poorer than usual.

(3) Again because of the low cranking speed, there is little manifold depression to encourage fuel vaporization.

179/ Harrow, p. 98.

> A consequence of this is that very rich mixtures must be used for starting and cold running, and these rich mixtures have a serious effect on the engine's fuel economy.

Repeated tests of Webster-Heise equipped engines, however, have shown no cold-start problems. Webster-Heise claims that this is because the vaporization rate is very high initially, even at ambient temperatures. Because enrichment is unnecessary with the Webster-Heise valve, cold-start emissions are very low (see Summary of Tests).

Because the torque is greater than standard, as discussed in the section on torque, performance is improved over baseline. One of the most chronic complaints about the new domestic cars being built today is that they have very limited power. Although some specialty cars forego fuel economy in favor of high compression ratios and lower gearing to regain better performance, most manufacturers seem to have accepted the loss of performance as a necessity to retain fuel economy gains. The Webster-Heise valve makes possible increases in both torque and fuel economy. During the ETC tests, the Webster-Heise car (on 75-octane fuel) was noted by the certified test driver as having consistently better driveability than the baseline car (see Summary of Tests).

Another characteristic observed in the tests is the resistance of the Webster-Heise valve to engine stalling and flooding. Because the Webster-Heise valve forces the gasoline to change state at low manifold temperatures, the charge is in a more combustible state for ignition in the combustion chamber. As a result, the air/fuel ratio does not have to be as rich as standard (because much more of the gasoline is in vapor form). Air /fuel ratios of 1:1 or 2:1 are normally needed to provide a reliable cold start in conventional engines. 180/ The reason most accelerators have to be pumped to start conventional automobiles is to force so much liquid gasoline into the manifold that enough gasoline vapor will evolve to permit stable combustion, although this greatly increases HC emissions.

Improvement in combustion stability at idle has also been observed as a characteristic of the Webster-Heise valve. Because the time available for combustion increases with a decrease in engine speed, the already slow combustion in standard engines is reduced to the point (around 500 RPM) where flame instability causes roughness and eventual stalling. Because the Webster-Heise valve appears to accelerate combustion, the idle limit can be lowered to a much lower speed (around 300 RPM) before instability appears. This could be especially important in reducing HC emissions and in increasing fuel economy in city and stop-and-go driving.

3. Engine Maintenance

There are a variety of problems which plague the standard engine and which can interfere with continued operation or, if severe enough, can cause engine failure. As discussed earlier, detonation is a most serious problem and is a common one in modern automobiles. Knock can cause serious damage to engine parts as well as limiting performance. Use of the Webster-Heise valve, as indicated in the test data in the Summary of Tests, appears to be even more effective than chemical additives in reducing this problem.

180/ Harrow, p. 98.

Removal of the additives from gasoline, especially tetraethyl lead (which is not combustible), can greatly reduce the amount of engine deposits formed and the contamination of catalytic converters. The use of lead-free gasoline, for example, greatly reduces combustion chamber deposits which, if not removed, can double the HC emissions with mileage. 181/ Spark-plug fouling from lead can also sharply reduce fuel economy. Removing lead, however, can cause other deposits to form in standard engines. The aromatics and other octane enhancers that are substituted for lead tend to form carbon deposits more readily than leaded gasolines. This eventually causes engine octane requirements to increase. Webster-Heise claims that its valve eliminates the need for either type of additive and greatly reduces the formation of engine deposits when additives are used.

The vaporization of the fuel itself is an important factor in reducing engine deposits. The part of the fuel that is not vaporized and burned will accumulate and form sludge, varnish, and other harmful deposits in the engine. 182/ These carbonaceous deposits are abrasive and greatly contribute to engine wear, especially if the unvaporized gasoline dilutes the lubricating oils. It was observed during testing of the Webster-Heise modified car that the crankcase oil stayed clean, even after extensive operation, indicating an absence of carbon deposits in the cylinders. Webster-Heise also reported that no oil was consumed or needed to be added, other than for infrequent oil changes. When the

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181/ Toboldt and Johnson, p. 235.

182/ Ibid., p. 232.

engine was disassembled after 80,000 miles of testing, not only were no engine deposits found but the expected cylinder wear of .0100 to .0150 inch was to be only .0025 which is within the normal factory tolerance (see Informal Testing, Summary of Tests). This represents a reduction in normal wear of between 75 and 83 percent. There was no appreciable crankshaft wear.

4. Catalytic Converter Operation

A long-standing concern in automotive pollution control has been the need to maintain exhaust temperatures high enough to "light off" unburned hydrocarbons in the exhuast. The Webster-Heise valve reduces the amount of HC left after combustion but, because of its higher thermal efficiency (less heat is transferred to the coolant because of the faster burn), it also produces exhaust temperatures that are somewhat higher (about four percent) than standard. This makes the catalytic converter more effective and extends its useful life because the volume of pollutants that it must treat is lower. This is also supported by the fact that the engine coolant temperature is lower than standard and exhaust temperatures are higher, indicating greater thermal efficiencies.

APPENDIX II

SUMMARY OF TESTS

TEST 1

Place: Ethyl Corporation
Ferndale, Michigan

Date: April 22, 1980

Equipment: Baseline car was a 1977 Chevrolet Nova with a 6 cylinder, 250 cubic-inch engine with a compression ratio of 8.17:1 W-H test car was 1979 Monte Carlo with a 6 cylinder, 250 cubic inch engine, with a compression ratio of 8.06:1.

Test: Standard Coordinating Research Council octane test on spark advance dynomometer.

Result: The W-H car ran with no ping at a steady-state speed of 50 MPH and achieved 28.7 MPG with a manifold vacuum pressure of 16.5 inches of mercury (Hg) compared to the baseline of 27.7 MPG with a manifold vacuum pressure of 14.8 inches of Hg (peak-to-peak).

The W-H car operated successfully on 81 RON (77 R+M 2) with 3 degrees more initial spark advance than the manufacturer's specification of 91 RON (87 R+M/2).

Distribution quality was measured and found to be improved over standard. No power loss was observed or measured.

TEST 2

Place: Automotive Testing Laboratories
Aurora, Colorado

Date: May 8, 1980

Equipment: W-H test car was a 1979 Monte Carlo with a 6 cylinder, 250 cubic-inch engine with a compression ratio of 8.06:1.

Test: Fuel economy

Result: Fuel economy was 30.1 MPG with 14 degrees initial spark advance and no ping. Manufacturers specification is 8 degrees.

TEST 3

Place: Environmental Testing Corporation
Aurora, Colorado

Date: August 15-26, 1980

Equipment: W-H test car was a 1979 Monte Carlo with a 6 cylinder, 250 cubic inch engine with a compression ratio of 8.06:1. The baseline was provided by the same car without the device. No exhaust gas recirculation (EGR) or catalytic converter was used on either car.

Test: 50-MPG steady-state test.

Test: EPA cold-start city test.

Result:

	FUEL ECONOMY	HC gm/mi	CO gm/mi	NOx gm/mi	DRIVEABILITY	AVG CVS TEMP F
Webster-Heise 20 Advance 75 Octane	18.835	2.701	33.876	2.570	GOOD	83.6
BASELINE 11.5 Advance 97 Octane	17.253	3.002	42.029	3.819	POOR	81.0

With 75-octane fuel (W-H) the ping point was 2 degrees after TDC. With 97-octane (baseline) it was 8 degrees before TDC, confirming test vehicle variation for ping.

TEST 4

Place: Environmental Testing Corporation
Aurora, Colorado

Date: October 14-15, 1980

Equipment: Same as Test 3.
Timing was set at 13 degrees initial advance.

Test: EPA Highway test.

Witnessed by representatives of General Motors, Ford, Chrysler, Sohio, Chevron, Cities Service, Marathon, Texaco, Amoco, Gulf, ARCO, Gulf Science and Technology Co., Phillips, Heningson Durham and Richardson, the PACE Co., and the Swedish Embassy.

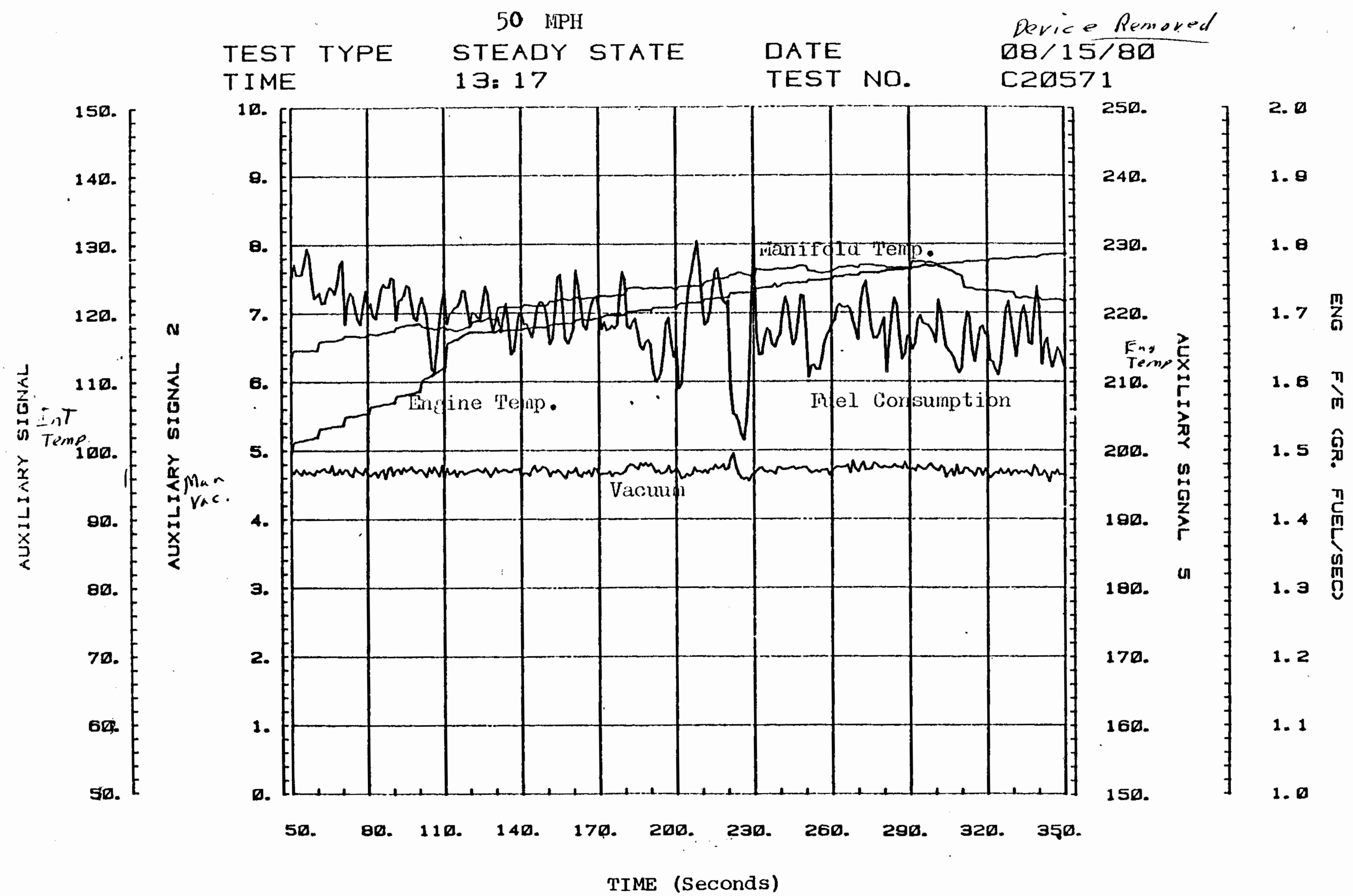

FIGURE 14. 50 MPH STEADY-STATE TEST (BASELINE)

Source: Environmental Testing Corporation

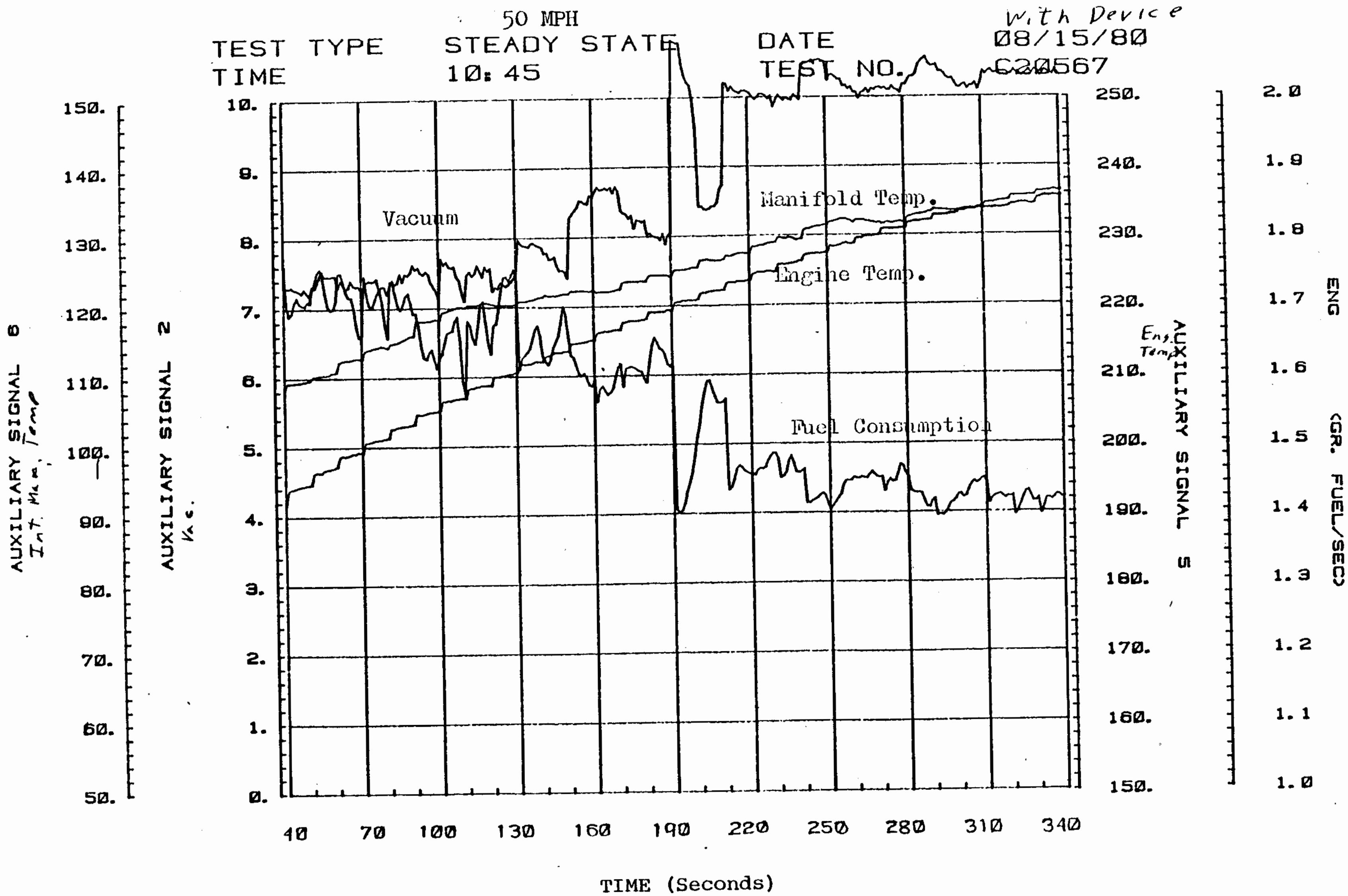

FIGURE 15. 50 MPH STEADY-STATE TEST (WITH WEBSTER-HEISE VALVE)

Source: Environmental Testing Corporation

Results:

W-H PRE-TEST (Oct. 14)

FUEL OCTANE	FUEL ECONOMY (MPG)	HC (gm/mi)	CO (gm/mi)	NOx (gm/mi)	AVG CVS TEMP (F)
75	25.607	1.253	11.255	3.971	80.6
85	23.608	1.517	24.635	4.417	79.1
97	24.108	1.324	13.172	4.847	77.6

SAME TEST REPEATED (Oct. 15)

FUEL OCTANE	FUEL ECONOMY (MPG)	HC (gm/mi)	CO (gm/mi)	NOx (gm/mi)	AVG CVS TEMP (F)
75	25.891	1.174	11.455	4.001	81.5
85	23.956	1.284	27.223	4.160	78.1
97	23.859	1.312	15.495	4.653	76.8

INITIAL SPARK ADVANCE WITHOUT KNOCK (Oct. 15)
(degrees before top-dead-center)

	INDOLENE (97 Octane)	ROAD FUEL (85 Octane)	BLENDED FUEL (75 Octane)
Webster-Heise	33	26	14
Baseline	25	16	3

Note: 1^{o} of spark advance equals 3/4 of an octane point.

TEST 5

Place: Ford Motor Co.
Engine Dynamometer Laboratory
Dearborn, Michigan

Date: January 26, 1981

Equipment: 2.4 liter 4 cylinder production Ford engine run on 78 RON (74 R+M/2) fuel with a compression ratio of 8:1, with and without the W-H valve.

Air fuel ratios were held constant at 13.3:1. All manifold vacuums were held constant at 8" hg for both engine systems.

Test: Torque, fuel economy, and spark advance (octane requirements) tests were conducted at 8 inches of manifold vacuum and at wide-open throttle on an engine dynomometer.

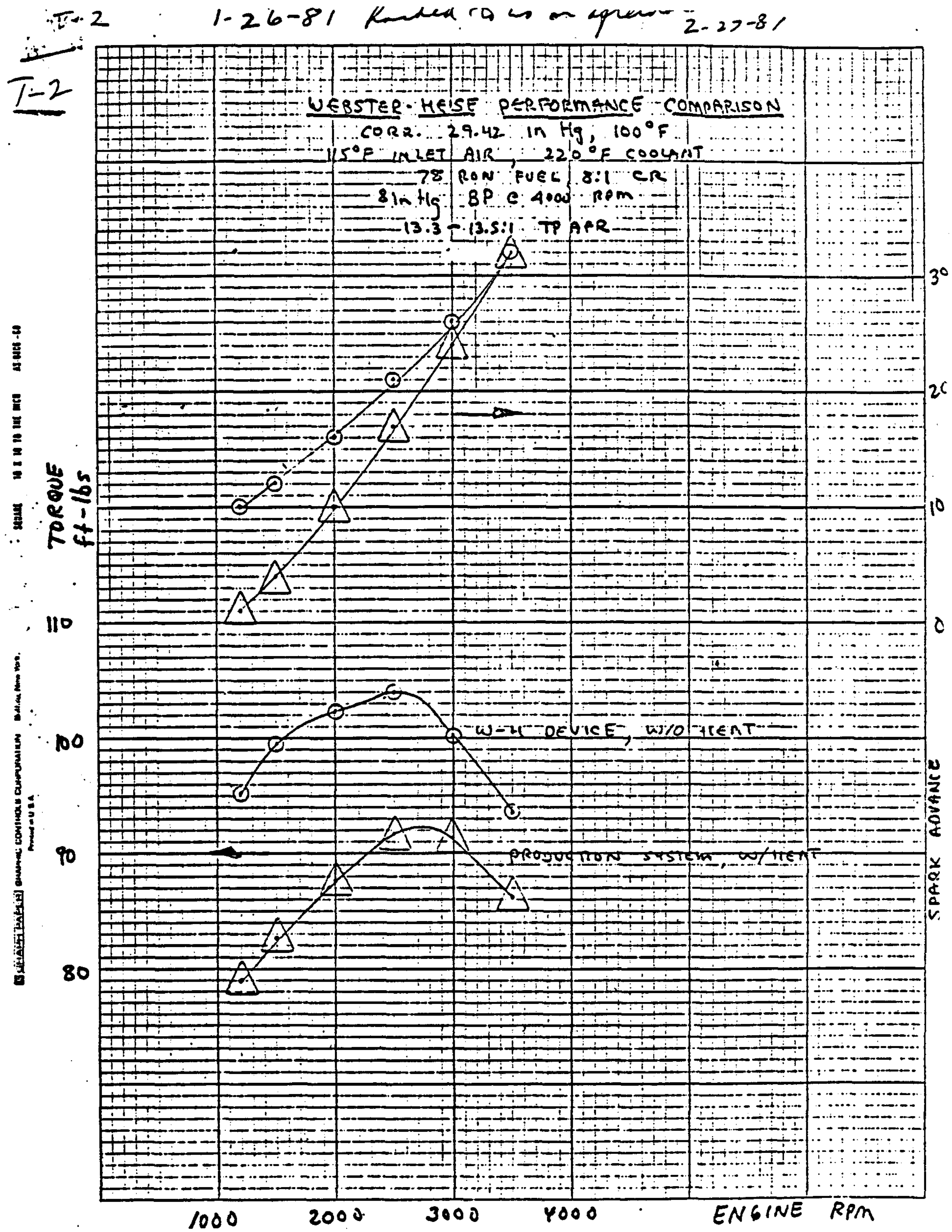

FIGURE 16. TORQUE COMPARISON TEST (WEBSTER-HEISE VALVE VERSUS FORD PRODUCTION SYSTEM)

Source: Ford Motor Co.

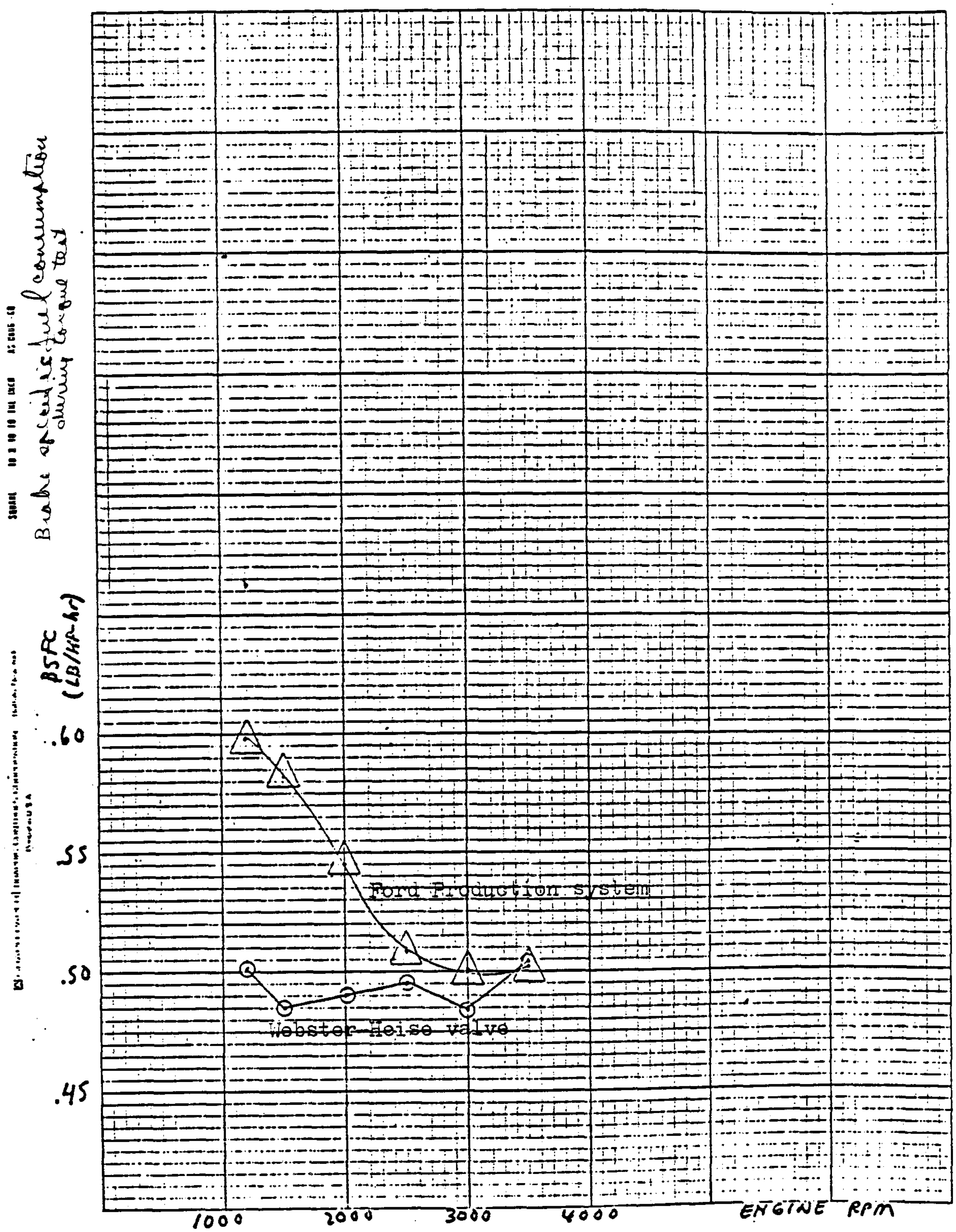

FIGURE 17. FUEL CONSUMPTION DURING TORQUE TEST (WEBSTER-HEISE VALVE VERSUS FORD PRODUCTION SYSTEM)

Source: Ford Motor Co.

INITIAL SPARK ADVANCE WITHOUT KNOCK (T-2)
(degrees before top-dead-center)

RPM	PRODUCTION SYSTEM (WITH HEAT)	W-H SYSTEM (WITHOUT HEAT)
1200	1	10
1500	4	12
2000	10	16
2500	17	21
3000	24	26
3500	32	32

TORQUE TEST (T-2)
(ft/lbs)

RPM	PRODUCTION SYSTEM (WITH HEAT)	W-H SYSTEM (WITHOUT HEAT)
1200	79.0	95.0
1500	83.0	99.5
2000	87.8	102.5
2500	91.8	104.0
3000	91.2	100.1
3500	86.0	93.5

BRAKE SPECIFIC FUEL CONSUMPTION DURING TORQUE TEST (T-2)
(bs/hp-hr)

RPM	PRODUCTION SYSTEM (WITH HEAT)	W-H SYSTEM (WITHOUT HEAT)
1200	.598	.500
1500	.583	.485
2000	.595	.490
2500	.510	.495
3000	.500	.485
3500	.510	.510

T3-17

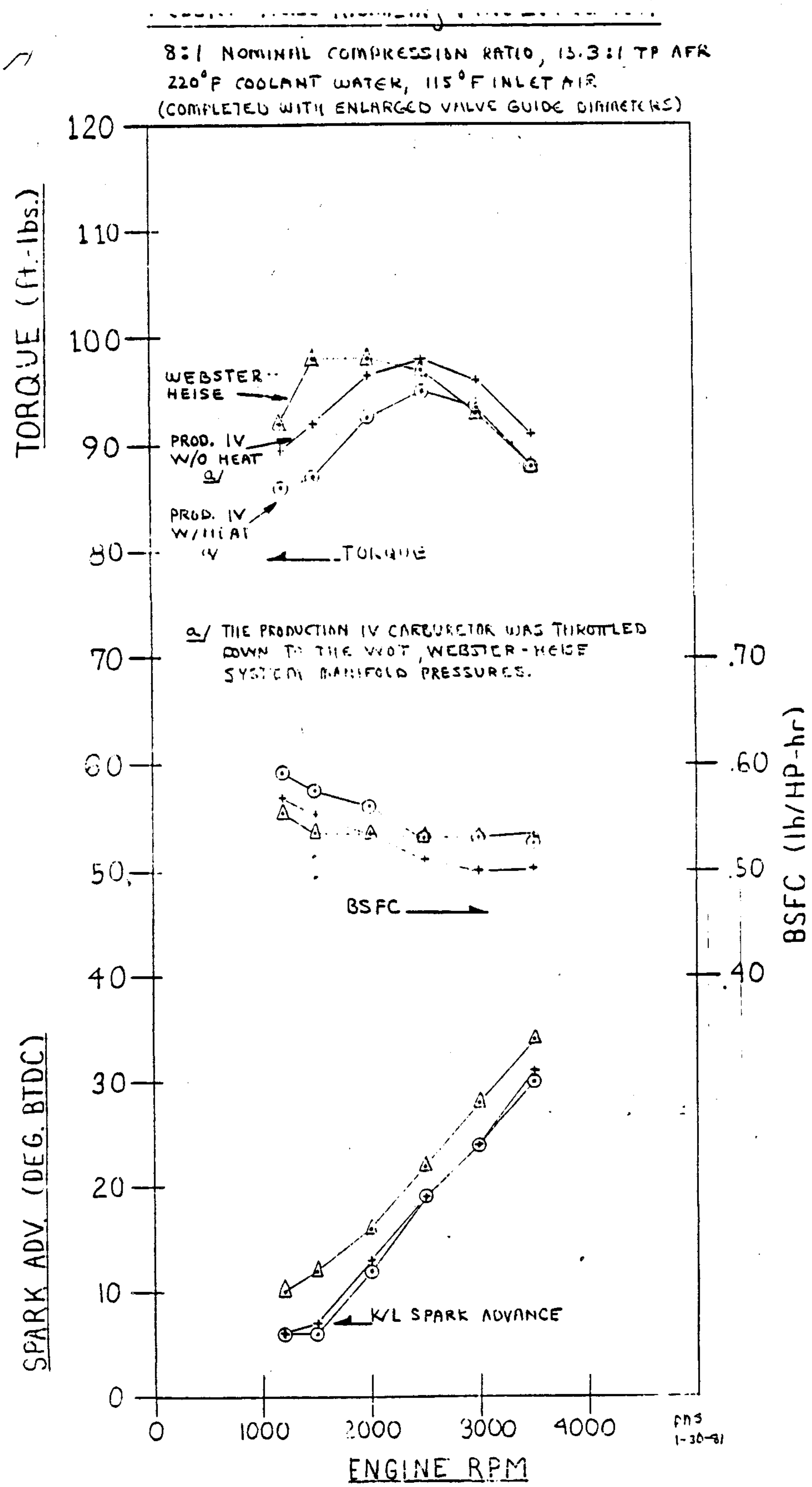

FIGURE 18. ENGINE PERFORMANCE COMPARISON (WEBSTER-HEISE AND FORD)

Source: Ford Motor Co.

TORQUE TEST (WOT) (T-3A)
(ft-lbs)

SYSTEM	1200 RPM	1500 RPM	2000 RPM	2500 RPM	3000 RPM	3500
Production w/heat	86	87	93	94	93	88
W-H w/o heat	92	98	98	96	93	88

BRAKE SPECIFIC FUEL CONSUMPTION DURING TORQUE TEST (T-3A)
(bs/hp-hr)

SYSTEM	1200 RPM	1500 RPM	2000 RPM	2500 RPM	3000 RPM	3500 RPM
Production w/heat	.59	.58	.56	.53	.53	.52
W-H w/o heat	.55	.53	.53	.53	.53	.53

INITIAL SPARK ADVANCE WTHOUT KNOCK (T-3A)
(degrees before top-dead-center)

SYSTEM	1200 RPM	1500 RPM	2000 RPM	2500 RPM	3000 RPM	3500 RPM
Production w/heat	6	6	12	19	24	30
W-H w/o heat	10	12	16	22	28	34

TEST 6

Place: Environmental Testing Corporation
Aurora, Colorado

Date: July 10 - July 12, 1982

Equipment: 1982 Oldsmobile Cutlass Supreme, 231 cubic-inch 3.8 liter V-6, 8:1 compression ratio. NOTE: The 3-way converter was recalled by General Motors during the test.

Test: Torque tests were conducted at steady-state wide-open throttle. EPA highway economy tests were conducted with 10.3 hp road load. All tests were conducted with standard manifold heat and all pollution control equipment was operational. The manifold was not cooled on the Webster-Heise modification and the electronic carburetion and closed loop calibrations were not altered.

TORQUE
(ft-lbs)

MPH (WIDE-OPEN THROTTLE)	BASELINE 97 OCTANE	BASELINE 75 OCTANE	WEBSTER-HEISE 75 OCTANE
30	126	93	130
40	100	78	109
50	86	72	90

VACUUM
(inches of Hg)

MPH (WIDE-OPEN THROTTLE)	BASELINE 97 OCTANE	BASELINE 75 OCTANE	WEBSTER-HEISE 75 OCTANE
30	.5	.4	1.2
40	.5	.5	1.3
50	.6	.7	1.6

INITIAL SPARK ADVANCE WITHOUT KNOCK
(degrees before top-dead-center)

MPH (WIDE-OPEN) THROTTLE	BASELINE 97 OCTANE	BASELINE 75 OCTANE	WEBSTER-HEISE 75 OCTANE
30	16.0	3.0	19.0
40	16.5	5.0	22.5
50	18.5	7.5	24.0

HIGHWAY ECONOMY TEST--ENGINE*

ENGINE	NOx (grams)	HC (grams)	CO (grams)	FE (MPG)
BASELINE 97 OCTANE	15.051	22.784	90.274	31.414
WEBSTER-HEISE 75 OCTANE	8.272	19.733	76.046	35.614

*Measured at the exhaust manifold prior to catalytic conversion.

HIGHWAY ECONOMY TEST--BAG*

ENGINE	NOx (grams)	HC (grams)	CO (grams)	FE (MPG)
BASELINE 97 OCTANE	.103	.034	1.627	31.414
WEBSTER-HEISE 75 OCTANE	.098	.076	1.316	35.614

*Measured after catalytic conversion
(Note: The Three-way converter was in recall at the time of the test. The baseline testing was done first and may have contaminated the converter prior to the Webster-Heise test. The HC reading in particular may have been affected as indicated by the low engine-out reading for HC during the same test in the table above).

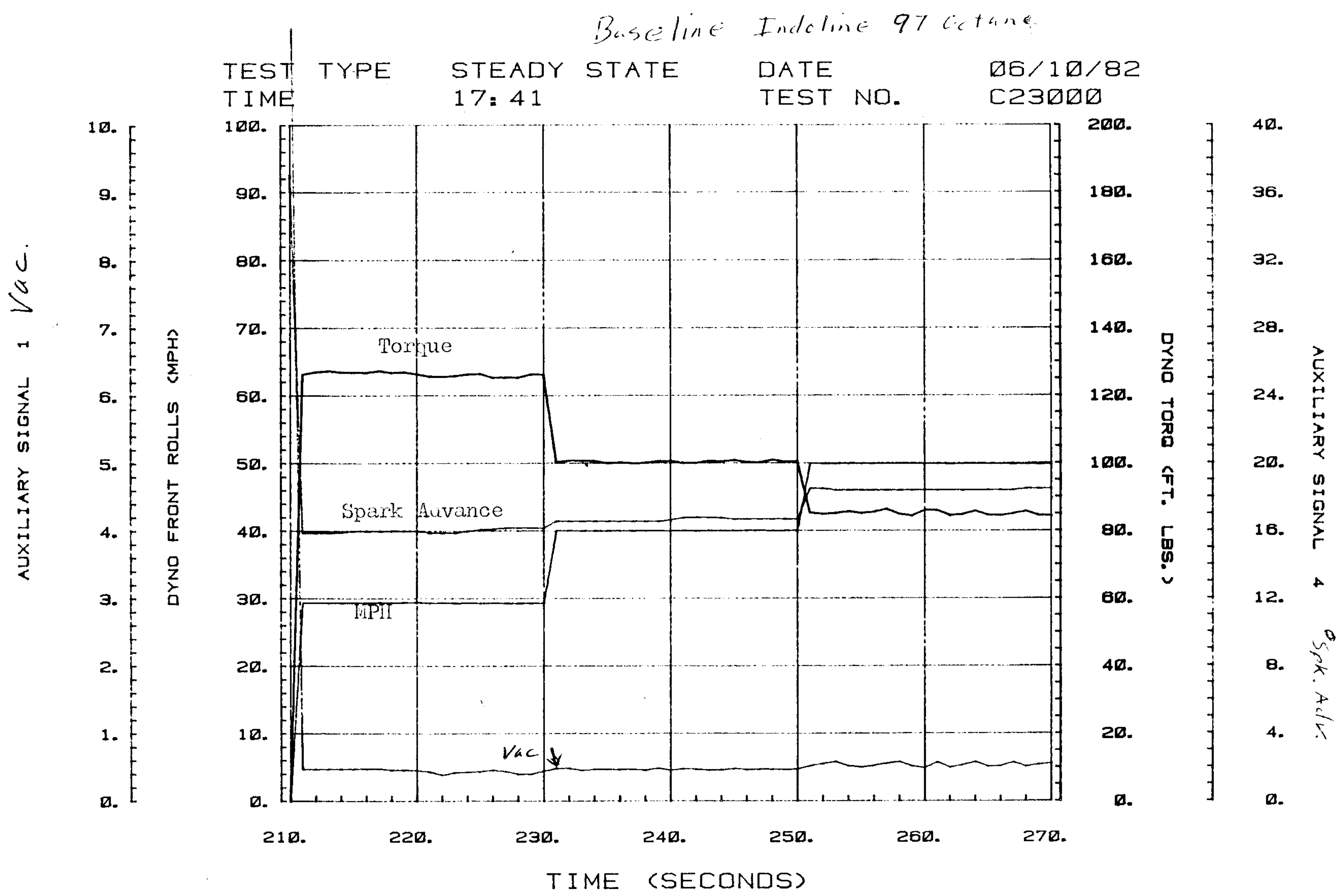

FIGURE 19. TORQUE TEST AT WIDE-OPEN THROTTLE (BASELINE W/O VALVE, 97 OCTANE)

Source: Environmental Testing Corporation

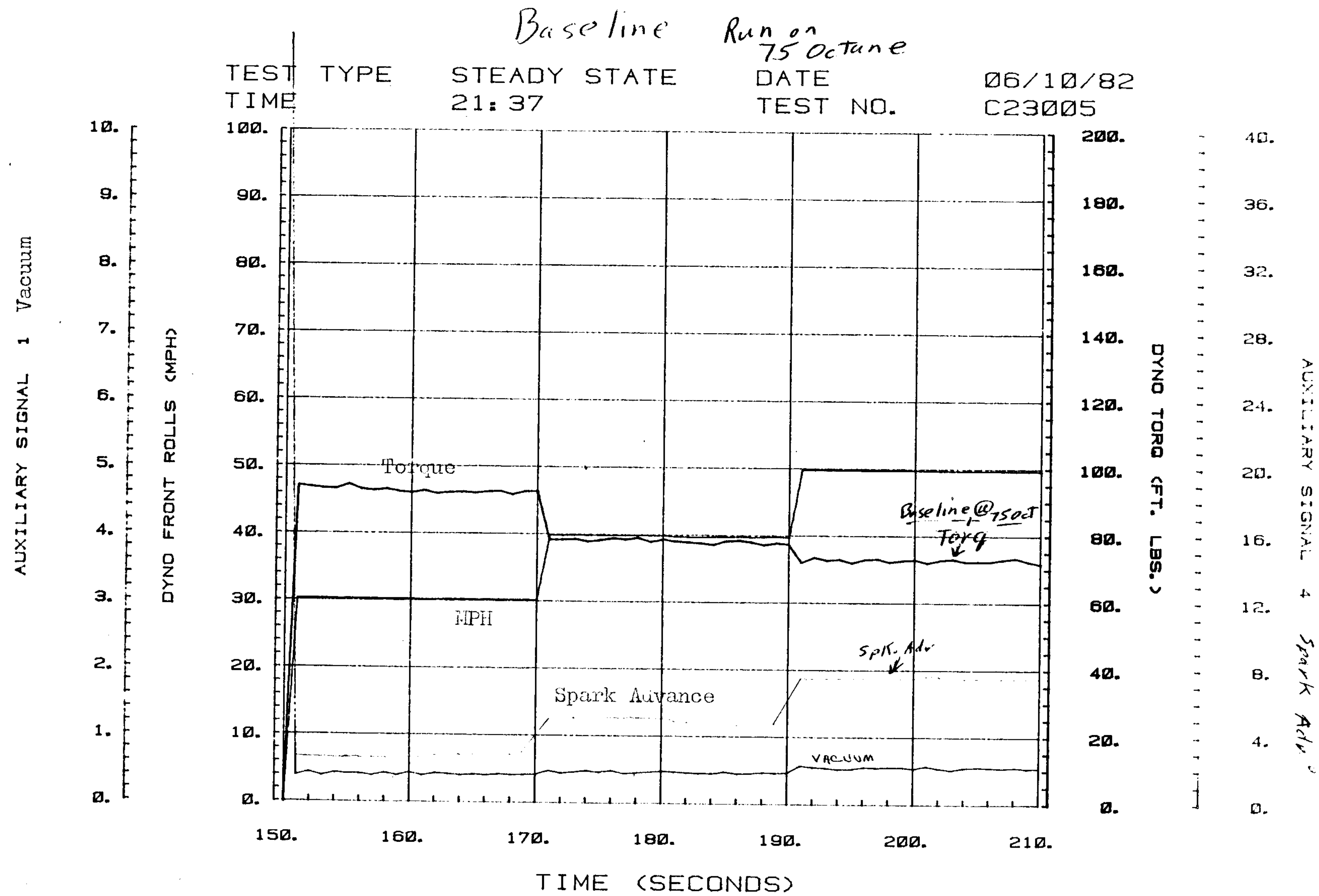

FIGURE 20. TORQUE TEST AT WIDE-OPEN THROTTLE
(BASELINE W/O VALVE, 75 OCTANE)

Source: Environmental Testing Corporation

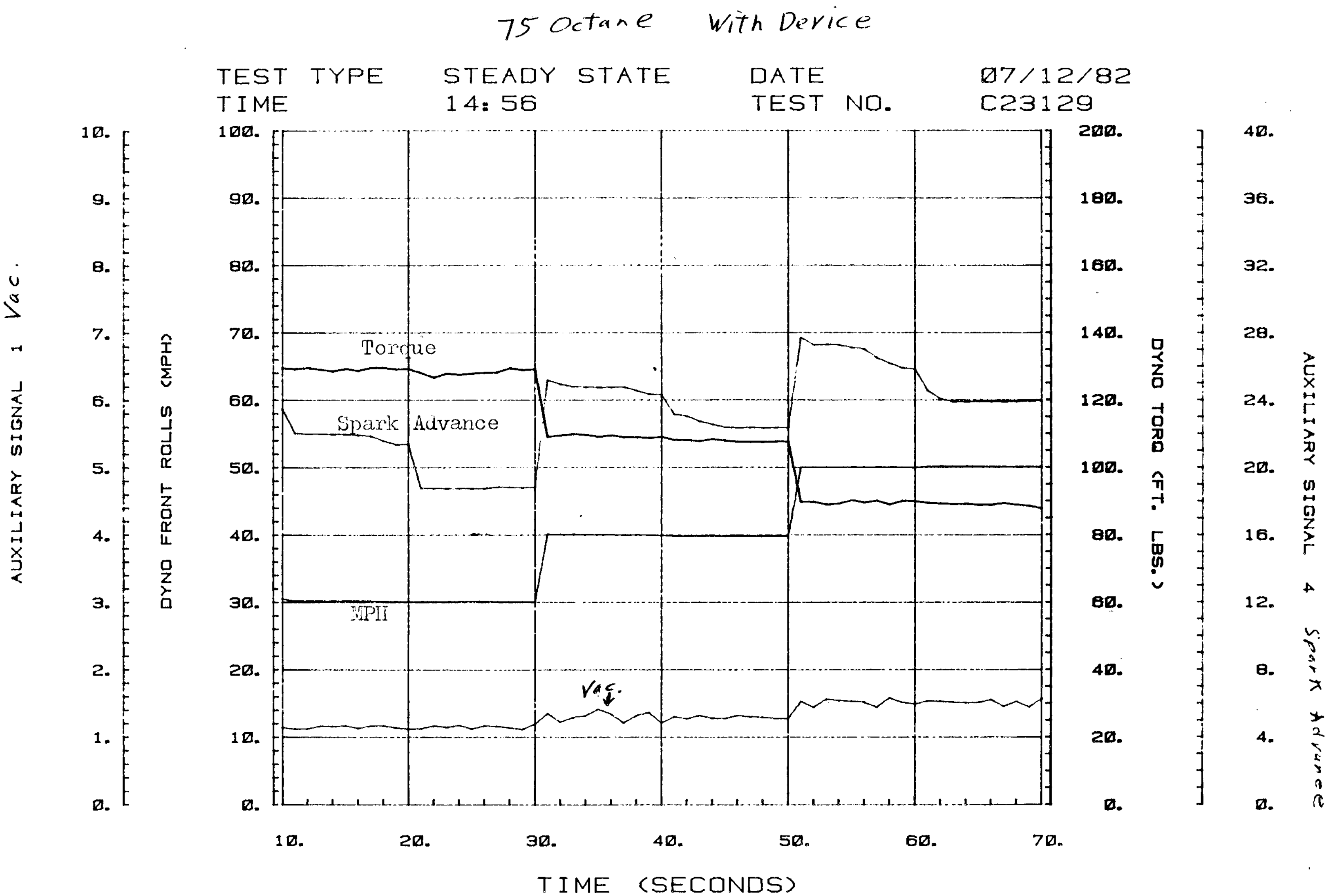

FIGURE 21. TORQUE TEST AT WIDE-OPEN THROTTLE (WITH WEBSTER-HEISE VALVE, 75 OCTANE)

Source: Environmental Testing Corporation

ENVIRONMENTAL
TESTING
CORPORATION

July 27, 1982

Mr. David Lindahl
CRS - ENR
Library of Congress
Washington, D.C. 20540

Mr. Lindahl:

This letter is to certify that the test results of the Webster-Heise modified cars tested at the Environmental Testing Corporation laboratory are correct as stated in the Summary of Tests (Tests 3, 4, and 6). All tests were run in conformance with established EPA equipment requirements and procedures and with the settings, fuels, and equipment indicated. ETC is fully recognized by the EPA to conduct these tests. In all of the tests run at ETC, the Webster-Heise cars (in comparison to the same cars unmodified) achieved better fuel economy, lower emissions, and better driveability on fuels with at least ten (10) points lower octane. No loss of torque was apparent as evident through tests performed during July, 1982.

Sincerely,

Albert Papay
President

ALP/jef

1859 JASPER STREET •• AURORA, COLORADO 80011 •• (303) 344-5470

INFORMAL TESTS AND OBSERVATIONS BY THE WEBSTER-HEISE CORPORATION

During the development of the Webster-Heise valve, numerous in-house road tests (totalling over 100,000 miles) were conducted. Several test cars (including a Chevrolet Monte Carlo, Chevrolet Monza, and an Oldsmobile Cutlass Supreme) were used which, in addition to the data obtained in the formal tests, provided some information about the use of the valve. The disassembly of the Monte Carlo engine after 80,000 miles of testing also provides some interesting insight into the workings of this device. These observations were made by the Webster-Heise Corporation and are included here as an unverified supplement to the formal test data.

Fuel economy in road tests increased by 15 to 25 percent.

Driveability was improved with considerably more response at low RPMs and a lighter throttle was required.

Cold starts were greatly improved with the valve. The modified car would start cold with no choke and would sustain combustion. The same car, unmodified, would not start without choking and stalled at least once with it.

No engine deposits were detected when the engine was disassembled after 80,000 miles (including many miles at high temperatures on dynometers). Cylinder wear was only .0025 inch instead of the .0100 to .0150 inch that would normally be expected. Crankshaft wear was not apparent.

No lubricating oil was consumed except for extended-interval oil changes. No discoloration or contamination of the oil was detected.

Coolant water temperature was lower than normal. One-third of the radiator was covered to bring the engine temperature to the desired level of 195 F.

The Monte Carlo (with the valve) was run successfully on a blend of 50 percent methanol and 50 percent 87-octane gasoline with no loss of performance. Methanol has poorer cold-start characteristics than gasoline and its use as a fuel seemed to be facilitated by conditioning with the valve. Kerosene (33 percent) and gasoline (67 percent) have also been used successfully.