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LAWRENCE
LIVERMORE
LABORATORY

LASER IMPLOSION DYNAMICS

DISTRIBUTION STATEMENT 1

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ABOUT THE COVER

A laser-driven implosion of a DT-filled hollow glass target photographed in the 1.5-keV x-ray band of light emitted by silicon. The image was formed by a grazing-incidence-reflection x-ray microscope, and then color-enhanced by computer to show details of the density distribution.

The 75- μ m-diam target was irradiated on both sides by 13-J, 62-ps beams of 1.06- μ m radiation from the Janus laser. The outer partial ring in the picture represents x radiation generated at the target wall at the start of the implosion. The bright central core represents a burst of x rays from the compressed target near the peak of the implosion.

Time-integrated pictures like this show the start and end of the implosion process, but they do not show the time history of the compressing target. For information about a new pinhole/streak camera combination that follows the entire implosion process, see the article beginning on page 1.

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BRIEFS

LASERS AND LASER APPLICATIONS

Imaging Implosion Dynamics: The X-Ray Pinhole/Streak Camera

We have developed an x-ray-sensitive pinhole/streak camera combination to photograph the implosion dynamics of laser-irradiated fusion targets.

SCIENCE AND TECHNOLOGY

The Methanol Engine: A Transportation Strategy for the Post-Petroleum Era

A methanol-based transportation system may be a long-term solution to the nation's petroleum energy problem.

ENVIRONMENT, HEALTH AND SAFETY

Phantom Construction: Building a Torso Manikin for Whole-Body Counting

In building model torsos (phantoms) for whole-body counting studies, we have used laboratory materials to simulate human tissue. This article describes the development of these tissue simulants and the construction of the first model.

ADVANCED ENERGY SYSTEMS

National MFE Computer Center: 1976 Update

The MFE computer center at LLL added a seventh user service center this past year and improved its software, hardware, and data communication network.

NOTES AND REFERENCES

SEMIANNUAL INDEX

Livermore, California 94550

Briefs

The short items on this page announce recent developments of importance. Some of these items may be amplified in future issues; none of this material is reported elsewhere in this issue.

NEW SOLAR CELL APPROACH

We are starting development of a new scheme for producing cadmium sulfide solar cells that promises to make them bigger, more efficient, and less expensive. Preliminary proof-of-principle cells made by this process are already nearly competitive with production-quality cells made by conventional methods.

The conventional wet-dip method for making cadmium sulfide cells has been in use for more than a decade. In this process, a layer of cadmium sulfide on an inert backing is dipped briefly into a temperature-controlled bath containing copper chloride. The copper chloride attacks the cadmium sulfide surface, exchanging copper for cadmium and producing a thin layer of copper sulfide over the cadmium sulfide layer. Washing off the excess copper chloride solution, drying, and attaching electrical connecting leads completes the cell. There are many critical steps in the process, each of which can affect the cell's efficiency, stability, or output voltage.

In our new approach, reactive sputtering deposits an easily controlled layer of copper sulfide over the cadmium sulfide layer. The reactive sputtering technique is well developed, figuring in such applications as integrated circuit construction and special optical coating manufacture. This process does not attack the cadmium sulfide surface, but covers it gently with a uniform blanket. The process takes place in a vacuum, eliminating the dipping, washing, and drying steps of the wet-dip process. Even the lead attachment step could be done in vacuum by well-established vapor-deposition methods long familiar to makers of microminiature circuit components. It should be possible to automate all steps of the process, further reducing the cost.

The illustration compares the performances of different solar cells: silicon, wet-dip cadmium sulfide, and present (unoptimized) and projected dry-process cadmium sulfide. Solar cell performance hinges on two main factors, short-circuit current density (mA/cm^2) and open-circuit voltage (V). A good silicon cell gives about $32 \text{ mA}/\text{cm}^2$ and 0.6 V at 15% efficiency. The best wet-dip cadmium sulfide cells give about

$21 \text{ mA}/\text{cm}^2$ and less than 0.5 V at 8% efficiency. Our present (unoptimized) dry-process cells have only 4% efficiency and give only about $13 \text{ mA}/\text{cm}^2$, but they already match or surpass the best wet-dip cells in open-circuit voltage. Some of them, at 0.75 V , are already better in this respect than the silicon cells; they also should be more economical. Cadmium sulfide cells are theoretically capable of giving $35 \text{ mA}/\text{cm}^2$ and 1 V , with an efficiency of 20%, giving them considerable potential for improvement. The goal of our development over the next few years is to improve both the current density and the efficiency of these cells and to lower their cost, making them an economically competitive source of solar power.

Performance characteristics of various solar cells. Silicon cells (dotted curve) give the highest current density and have the highest efficiency. Wet-dip cadmium sulfide cells (solid curve) come next. Preliminary proof-of-principle cadmium sulfide cell specimens made by our dry process (solid blue curves) have low efficiency, but they already surpass the wet-dip cells, and in some instances the silicon cells, in open-circuit voltage. The projected performance of our cells after development (dashed blue curve) far exceeds that of the wet-dip cells, and would be highly competitive with silicon cells, especially on a cost basis.

Fig. 3. Alignment scheme for space-time studies of x-ray emission with the pinhole streak camera. Light from a helium-neon laser goes through a system of lenses, a filter, and a diagonal mirror to an x-ray-transparent pellicle that reflects about 50% of the alignment-laser beam. The angle of the pellicle is adjusted to make the laser beam appear to come from the center of the streak-camera slit. The beam passes through the glass of the composite x-ray pinhole assembly, through the transparent laser target, and into a telescopic viewer. We adjust the focusing lens and the beam clipping to produce a diffraction pattern between the pinhole and the laser target. Then both the pinhole assembly and the laser target can be centered accurately on the diffraction pattern.

measurements provide time-dependent implosion velocities, the best data for meaningful comparisons with numerical simulations.

A new pinhole/streak camera arrangement (Fig. 1) gives us time and space resolution in the same picture, i.e., velocity information. At the left, next to the imploding target, is the x-ray pinhole that forms a 50-times-magnified image of the target on the front slit of the streak camera. The x-ray streak camera, on the right, is based on a modified image converter tube.

X rays from the laser-irradiated target — striking i.e. 10-nm-thick, slit-shaped gold photocathode of the image converter tube — release slow secondary electrons from the cathode. Shaped electrostatic fields accelerate these electrons and focus them into a horizontal line image on the output phosphor screen. Meanwhile, a rapidly rising voltage pulse applied to deflection electrodes in the tube sweeps the line image vertically across the phosphor screen, so things that happen at different times appear at different places in the resulting streaked image. The time resolution of the camera is 15 ps.

When we use the streak camera without the pinhole, the streak data reveal the history of the x-ray intensity emitted during the implosion, but the record contains no detailed information about the spatial motion of the target envelope. Only with the addition of x-ray imaging can we obtain the additional important data on implosion speed.

The pinhole/streak camera combination provides accurate data only when all the elements are aligned within a few micrometres. As can be seen in Fig. 1,

raising the pinhole just a few micrometres would displace the diameter of the compressed-target image far enough from the streak camera slit that accurate implosion data would not be obtained. Alignment to such precision is difficult, but we have developed the techniques that make it possible.

The alignment problem is composed of several interrelated factors. To start with, the glass microsphere targets are small, and the implosion compresses them to a fraction of their original diameter. The small size of the compressed target means that the pinhole must be as small as possible to be able to image details on the target. The use of short-wavelength x rays makes it possible to use very small pinholes to obtain high resolution without losing image quality because of diffraction.

Unfortunately, there are no sources of suitable x rays intense enough to be used for alignment. When we try to use our standard helium-neon laser to align the small pinhole, we run into severe diffraction problems. The wavelength of this laser's red light is too large a fraction of the pinhole diameter, and the resulting image is too diffuse to permit accurate alignment.

We solved this problem by making pinholes that look small at x-ray wavelengths and large in visible light. This is feasible using a special glass. A 9- μ m-thick piece of this glass transmits only 0.001% of the x rays but is relatively transparent to visible light, transmitting 13% of the helium-neon laser light.

Figure 2 gives three views of the finished pinhole assembly. The body of the assembly is a 16-gauge hypodermic needle with the end cut off squarely. We

Fig. 4. Space-time record of three implosions made with the pinhole/streak camera combination. The colored lines are contours of equal film density, i.e., of equal x-ray intensity. Vertical arrows indicate implosion times; horizontal arrows show initial target diameters. The small white rectangle in each frame shows the resolution element, $6 \mu\text{m}$ wide and 15 ps tall. The dashed white lines correspond roughly to trajectories of the target surfaces in space-time; curved trajectories indicate acceleration.

In the implosions recorded on July 2 and 8 (above) the target was irradiated from both sides. These symmetrical implosions reached speeds of 310 km/s and generated 10^6 neutrons. In the experiment of July 9 (lower left) the beam on the left was purposely blocked. The implosion reached a velocity of 280 km/s and generated about 2×10^5 neutrons. Although the implosion was one-sided, the subsequent explosion was two-sided, in agreement with numerical simulations.

mount a $12\text{-}\mu\text{m}$ -thick gold foil across the end of the needle and mechanically drill a $125\text{-}\mu\text{m}$ -diam hole in it. This forms the visible-light pinhole. Then we cement a $9\text{-}\mu\text{m}$ -thick disk of the x-ray-absorbing glass over the gold foil and laser drill a tiny hole in the glass, concentric with the $125\text{-}\mu\text{m}$ hole. This forms the x-ray pinhole.

Having made the composite pinhole, we still have to align all the elements of the system. We do this by inserting an x-ray-transparent optical beam splitter as shown in Fig. 3. We adjust the focusing lenses and the angle of the beam splitter so that the laser light projected through the $125\text{-}\mu\text{m}$ pinhole appears to be coming from the center of the streak-camera slit.

We also clip the light beam at the focusing lens in such a way as to produce a diffraction pattern — a bull's-eye array of light and dark concentric rings — midway between the pinhole and the laser target. We

can then move the holder assembly until the $125\text{-}\mu\text{m}$ pinhole is centered on this pattern. This centers the small x-ray pinhole on the line-of-sight to within the 2- to $3\text{-}\mu\text{m}$ concentricity error. Then we move the laser target until it is also centered on the diffraction pattern, completing the alignment to an overall accuracy of $5 \mu\text{m}$.

With the pinhole camera aligned with the streak-camera slit, the streak camera records both x-ray production and x-ray source position, separating events in time so that the entire implosion and subsequent explosion can be followed. Figure 4 presents the records of three different implosion events, taken on different days last July. The original black-and-white images have been analyzed with a microdensitometer, and the resulting contour lines have been color coded to reveal details of the density distributions.

All three of these events took place on the Janus laser system, which generates 0.45-TW pulses of 1.06- μm light 70 ps long (FWHM). In the experiments of July 2 and 8, the targets were irradiated with two beams coming from opposite sides, making symmetrical implosions.

Several features of these records are evident. The colored lines are contours of equal density, i.e., x-ray intensity. The small rectangle in the lower right corner indicates the resolution element, about 6 μm wide and 15 ps tall. The scale along the bottom of each picture indicates the initial diameter of the D-T target.

The diagonal dashed lines represent the trajectories of peak x-ray emission in space-time. As such they provide characteristic velocities of the implosion process, which, according to our computer simulations, agree closely with the velocity of the target surface. The two incoming trajectories are curved, indicating that the surface was accelerating throughout the laser pulse. Straight trajectories would indicate a constant velocity.

The experiment on July 9 was purposely made asymmetrical. One of the laser beams was blocked so that the target was irradiated from the right only. The target thus is heated and implodes essentially from one side, with only one incoming trajectory. After convergence near the target center, there is a highly

asymmetric expansion with two lobes. The slopes of these trajectory lines indicate the compression and expansion velocities of the glass envelopes. (The camera observes radiation primarily from the shell rather than from the enclosed fuel.) In the one-sided implosion the incoming velocity was 280 km/s. In the symmetrical implosions the measured velocity reached 310 km/s, in good agreement with LASNEX calculations.

All three of these events produced neutrons, but the symmetrical implosions were more efficient, each producing 10^6 neutrons. The asymmetrical implosion produced only 2×10^5 neutrons.

Experiments such as these allow us to study the implosion process in much more detail and with far greater accuracy than ever before. They also provide basic data, for example implosion velocities, that can be compared with the predictions of theoretical calculations. These comparisons give us new information confirming the validity of the basic physics described in our codes. This information is already having an impact on our calculations and target designs and has increased confidence in our inertial confinement approach to fusion.

Key Words: implosions - measurement; laser-induced fusion; streaking cameras; x-ray microscopes.

SCIENCE AND TECHNOLOGY

THE METHANOL ENGINE: A TRANSPORTATION STRATEGY FOR THE POST-PETROLEUM ERA

Diminishing domestic petroleum resources and increasing demand for transportation fuels are creating a supply-demand gap in the U.S. that will become critical after the 1990's. For automotive transportation, this widening gap means spiraling gasoline prices and intensified pressure for the development of alternative fuels. Methanol is one of the more promising synthetic automotive fuels, and designing an engine to run specifically on methanol could further enhance its advantages. The following article looks at the properties of methanol that make it an attractive fuel and at the potential efficiencies of a stratified-charge engine designed for methanol operation.

As a nation, we face a widening gap between domestic oil supply and demand for that oil. As shown in Fig. 5, if we take even a conservative estimate of future petroleum demand, this shortage will become critical in the 1990's. Because of limited world oil supplies, massive oil imports in 2000 and beyond will be unable to fill the gap. The implications for automotive transportation are clear: gasoline prices will continue to rise and alternatives to our petroleum dependence must be found. Alternative fuels and

alternative propulsion systems are two possible means of closing the supply-demand gap (see box on p. 7.)

There are several possible alternative-fuel approaches. The most promising at the present time are:

- Gasoline or distillate from shale.
- Gasoline or distillate from coal.
- Methanol from coal.

Methanol may be the best synthetic automotive fuel for several reasons: it offers superior engine performance, it is cost-competitive with other synthetic fuels, its production technology is currently available, and it has potential for production from renewable resources.

Several heat-engine cycles are candidates for the methanol engine. Our exploratory work favors development of a high compression-ratio (14 to 16), open-chamber, stratified-charge engine with timed fuel injection and small to medium displacement (2 to 4 litres). This work also suggests that methanol would allow a stratified-charge engine to operate in its superior fuel-economy range and to meet emission standards. We estimate that a methanol-fueled stratified-charge engine that meets the 1978 emission standards will have a fuel economy gain of 44 to 71% over comparable conventional engines. Methanol is also an attractive fuel for advanced Brayton- and Otto-cycle (turbine and gasoline) engines.

Contact Harry C. Vantine (Ext. 7637) for further information on this article.

Fig. 5. Domestic production of oil and natural-gas liquids compared with national needs: a growing gap between oil supply and demand is inevitable. Domestic oil reserves here are estimated at 25×10^9 tonnes (182×10^9 bbl), with the area under the supply curve beyond 1974 adjusted to this estimate. Although U.S. demand for oil rose about 3.4% annually until 1973, conservation measures, shifts to other energy forms, and the increased cost of petroleum products should substantially decrease future demand. Our demand projection here is conservative, being based solely on population growth.

CLOSING THE PETROLEUM SUPPLY-DEMAND GAP

We have been studying the energy problem for some time and have noted that the liquid fuel problem – the petroleum problem – is a very important part of it; natural gas, of course, is also important. Even with very much reduced petroleum demand in the future – say one-half of traditional growth rates – a comparison of demand with domestic supply still reveals a substantial gap. The gap might be narrowed somewhat between now and 2000, but certainly after 2000 this gap will widen.

There are basically five ways to fill that gap. The first is to reduce the demand for mobility (in other words, drive less, go fewer places), and this solution will reduce petroleum demand. However, the resulting reduction in the standard of living, if it can be equated, is probably unacceptable to most people unless there is a clear state of emergency. A second option is to build smaller or more efficient cars. This also reduces the gap, but, although it postpones the inevitable, it doesn't solve the basic problem of petroleum depletion. The third option is to import more oil, which is what is being done for the most part now, and it temporarily solves the problem. But the world oil supply is limited, and our projections are that world oil production will peak around 2000. So increasing oil imports is not a long-term solution, either. The last two options – alternate fuels and alternate propulsion systems – offer the possibility of long-range solutions. Both are intermediate-term solutions if they are based on fossil fuels; but if they are based on renewable sources, they could be long-term, permanent solutions.

The Laboratory is looking at electric propulsion systems as well as at alternate fuels. The accompanying article summarizes one analysis of such a fuel – methanol – and looks at the theoretical potential of designing an engine to run specifically on this fuel. The prospects for substantially increased thermal efficiency with a stratified-charge engine designed for methanol appear promising.

Methanol as an Automotive Fuel

Methanol is quite different from current automotive fuels. It is chemically pure and thus has well-defined (as opposed to a range of) chemical properties. Furthermore, several of these chemical properties are very different from those of current gasolines and would permit significant engine design modifications to be considered (see Table 1).

High Octane Rating. Methanol has a high octane rating (Table 1), which permits its use in efficient high-compression engines. Compression ratios of 14:1 have been reported for Otto engines operating with methanol.⁴ Typical current production engines have compression ratios of 8:1 because of the low octane rating of unleaded gasolines.

Low Flammability Limit. Flammability limits are the extreme fuel-air ratios that will support flame propagation. Methanol's low flammability limit (Table 1) means that a flame will propagate into a relatively lean mixture of methanol and air. This makes methanol a good fuel candidate for lean-burn operation or for stratified-charge engines.

The practical effects of lean burn are low emissions and high efficiency. Lean-burn operation improves efficiency because of the dependence of γ (the ratio of specific heat at constant pressure to specific heat at constant volume) on temperature. With lean-burn operation, the working fluid has a lower temperature

and a higher γ ; this results in more energy for doing work and less energy for molecular excitations.

Clean Fuel. Methanol has a very low sulfur content since sulfur is removed before the methanol-synthesis step. Furthermore, methanol needs no lead additives to boost octane rating. Thus catalytic converters are not likely to be poisoned and will not produce sulfate in the exhaust.

Gasoline-fueled engines emit polynuclear aromatic hydrocarbons; methanol-fueled engines do not. Troublesome combustion-chamber deposits can also be eliminated or greatly reduced. This should lead to reduced maintenance costs.

Lower Flame Temperature. Methanol has a lower adiabatic flame temperature than does gasoline. This can result in considerably less heat loss to the exhaust and the coolant.

Burning Velocity. The velocity of the flame front with respect to the unburned gas is called the burning velocity or flame-propagation speed. The burning velocity depends on the air-fuel ratio, turbulence, and the proximity of surfaces.

At the stoichiometric ratio, the burning velocity of methanol is 21% higher than that of gasoline. This is due in part to the presence of hydrogen in the methanol flame. (Hydrogen is produced by methanol decomposition and has a very high burning velocity.)

The high burning velocity is important in lean-burning or stratified-charge engines. The decrease in burning velocity with lean fuel-air ratios in these engines is normally compensated for by increasing the turbulence intensity. Methanol fuel would provide an additional means of increasing burning velocity. Higher burning velocity also allows more spark retardation to control emission of nitrogen oxides.

The Methanol Engine

Alcohol has been used as a fuel for the internal combustion engine since the turn of the century. However, the literature contains few references to engines specifically designed for this fuel. No engine

has emerged as an alcohol or methanol engine in the sense that the gasoline engine is associated with the Otto cycle or the distillate engine is associated with the diesel cycle. Thus all possible configurations and cycles must be considered as candidates for the methanol engine.

Most of the data available on methanol operation in internal combustion engines were obtained in tests with conventional Otto-cycle engines. Exxon Research⁵ estimates that methanol operation in Otto engines would increase fuel economy by 26 to 38% relative to gasoline operation. Although no Otto engine optimized for methanol has yet been developed to substantiate these projections, significant efficiency improvements have been obtained by using methanol fuel.

Table 1. Physical properties of methanol and gasoline

Property	Methanol	Gasoline	Effect compared with using gasoline in current production engines
Chemical composition (wt%):			
Carbon	0.375	0.857	Lower CO and HC emissions; no polynuclear aromatic hydrocarbons; no sulfur; reduced combustion chamber deposits.
Hydrogen	0.125	0.143	
Oxygen	0.500	—	
Chemical formula	CH ₃ OH	C ₄ H ₁₀ to C ₁₂ H ₂₆	Decomposition to hydrogen; simpler kinetics.
Flammability limits (equivalence ratio)	0.61-3.0	0.78-4.5	Leaner burn (and therefore lower NO _x and CO emissions, higher fuel economy).
Energy content:			Larger fuel tank.
Lower heating value, MJ/kg (Btu/lb)	20.11 (8644)	44.38 (19,080)	
Stoichiometric mix, J/m ³ (Btu/ft ³)	2.87 (94.5)	2.84 (95.0)	
Vapor pressure at 311 K (100°F), kPa (psi)	32 (4.6)	55-83 (8-12)	Vapor lock.
Heat of vaporization, MJ/kg (Btu/lb)	1.10 (474)	0.35 (150)	More power and higher efficiency; difficulty in cold starting.
Octane number:			Higher compression ratio possible; no lead additives necessary.
Research octane number	106	86-93	
Motor octane number	92	77-84	
Cetane number	10	0-5	
Autoignition temperature, K	743	700-783	
Stoichiometric air-fuel ratio, kg air/kg fuel	6.46	14.55	Difficulty in atomizing fuel; more power at lower combustion temperatures.
Solubility for water at 293 K (68°F), ppm	Infinite	0.0?	Less NO _x ; internal engine cooling possible.
Density at 289 K (60°F), Mg/m ³ (lb/ft ³)	0.795 (49.7)	0.736 (46.0)	
Adiabatic flame temperature, K (°F)	2824 (4623)	2924 (4803)	Lower heat losses; less NO _x .
Boiling point, K (°F):	338 (149)		No methanol fuel on cylinder wall [if oil and coolant are above 338 K (149°F)]
10% point		348 (167)	
20% point		450 (350)

Fig. 6. Experimental data taken by Volkswagen Research⁴ with a four-cylinder engine. Significant efficiency improvements are obtained with methanol fuel, and these improvements are affected with no NO_x penalty; in fact, NO_x emissions decrease. These results lend credence to the projections of Exxon Research⁵ for increased fuel economy when methanol is used in conventional Otto engines. Compression ratios are given in parentheses.

Data obtained by Volkswagen Research⁴ on a four-cylinder Otto-cycle engine are shown in Fig. 6. Gasoline and methanol were run in an engine with a compression ratio of 9.7. Methanol operation showed higher efficiency and lower nitrogen-oxide emissions. When the compression ratio of the engine operating on methanol was raised to 14, the emission of nitrogen oxides decreased even further; methanol operation showed a 20% efficiency improvement over gasoline operation.

Methanol may allow stratified-charge engines to operate in their superior fuel-economy range and to meet emission standards. Stratified-charge engines operated on conventional fuels have shown efficiency gains but have had difficulty meeting exhaust emission standards. For methanol operation in a stratified-charge engine, a compression ratio of 14 to

16 can be used. This estimate is based on the fuel octane rating. Raising the compression ratio from 8 to 14-16 increases the efficiency by 16 to 23% relative to an Otto engine with a compression ratio of 8. (This increased efficiency is calculated for an ideal Otto cycle with a fuel/air mixture.)

The lean-burn advantages of the stratified-charge engine are at least as great with methanol as with gasoline. The Exxon results⁵ indicate that the advantage of using methanol may be 10% greater. We place the advantage of lean-burn operation at 28 to 47%.

Combining the effects of a higher compression ratio, lean-burn operation, and pollution control, the methanol stratified-charge engine offers a 44 to 71% energy economy relative to an Otto gasoline engine. Results for a methanol stratified-charge engine are summarized in Table 2.

Because of its low cetane rating, methanol does not appear to be a good fuel for diesel engines. It is known to be a good turbine fuel from experience with peaking turbines used for electric power generation. However, precise data are lacking, particularly for automotive engines.

The Stirling and Rankine external combustion engines are multifuel engines and can burn methanol. There appears to be no particular energy-economy advantage to methanol operation in these engines, however.

The composite fuel economies of several engine cycles are shown in Fig. 7. To place gasoline, methanol, and diesel fuels on a common energy basis, we have displayed fuel economy in km/equivalent litre (mi/equivalent gal), an equivalent litre being the volume of fuel that has the same energy as one litre of gasoline. The projections here are for a fleet with the current market distribution (29% full-size, 36%

Table 2. Energy economy of a methanol stratified-charge engine relative to a conventional gasoline engine with a compression ratio of 8

Effect	Advantage, %
Higher compression ratio	16-23
Lean-burn operation	28-47
Pollution control	0-1
System advantage	44-71

intermediate, and 35% small cars) over a composite (urban-highway) driving cycle. Furthermore, the comparison of different engines is on a common performance basis. All cars are assumed to be equipped with emission controls sufficient to meet the Clean Air Act standards — with the exception of the diesel, which does not appear capable of meeting the 0.4 g/mi limit for nitrogen oxides. As shown in Fig. 7, the methanol stratified-charge engine is superior to all engines except the Stirling in fuel economy and is equal or superior to the Stirling itself.

Development of a stratified-charge engine requires a more detailed understanding of combustion chamber events than is provided by traditional empirical engine-design procedures. Multidimensional computer models coupled with detailed measurements of engine processes can provide this detailed information. These new techniques open opportunities never before used extensively in engine research.⁷

Cost and Availability of Fuels

In the past the strongest barrier to the use of alcohol as fuel has been fuel cost, not utilization technology. Many estimates of synthetic fuel costs have been published by different authors in recent years. Such estimates have been made for a wide variety of

processes used to produce a variety of fuel products from coal or oil shale.

In comparing the costs of various fuels, such as synthetic gasoline and methanol, it would be desirable to use the published estimates. Unfortunately, such a comparison is not straightforward. Different authors will produce varying cost estimates even for the same process and product, because they do not necessarily use the same assumptions for capital and operating costs or the same methods of estimation.

We have taken the figures for capital investment, operating costs, and by-product credit as given by a number of authors, inflated them to 1975 dollars, and calculated the costs of synthetic fuels using the following accounting factors:

Financing method, % of equity	100
Internal rate of return (discounted cash flow), %	12
Project life, years	25
Depreciation schedule, years	16 (sum of digits)
On-line service factor, %	90
Corporate income tax, %	48
Average construction investment period, years	1.875

Fig. 7. Comparison of the methanol engine with other designs. Fuel economy here is measured in km/equivalent litre (mi/equivalent gal), an equivalent litre being that volume of fuel with the same energy as one litre of gasoline. Gasoline data are from the RAND Corporation.⁶ The Otto engine with methanol is projected to yield a 26 to 38% fuel economy advantage⁵; experimental data, such as that shown in Fig. 6, support this projection. The stratified-charge engine with methanol is projected to yield a 44 to 71% fuel economy advantage. This would make it a close competitor with the Stirling engine and far superior to all other designs considered here.

Table 3. Cost of synthetic fuels compared with gasoline

Source	Fuel	Cost per GJ (10^6 Btu) at pump, ex taxes (1975 dollars)		
		Strip-mined	Shaft-mined	<i>In situ</i>
Crude oil @ \$75/tonne (\$10/bbl)	Gasoline (U.S. 1975 average price)	—	—	3.72 ^a
Crude oil @ \$100/tonne (\$14/bbl)	Gasoline	—	—	4.50 ^a
Shale	Gasoline	—	4.05	3.50
Coal	Synthetic gasoline	4.80-5.15	—	—
Coal	Methanol	5.75-5.95	—	3.90

^aCrude oil is listed in the *in situ* column here because it leaves the ground in a liquid state ready for refining.

All synthetic-fuel costs are based on a western coal cost of \$7.70 per tonne (\$0.40 per 10^6 Btu). Published estimates of refining and average distribution costs for gasoline are inflated to 1975 dollars and added to the syncrude at-plant costs. Distribution costs for methanol are based on transporting via pipeline a proportionately larger volume of methanol per unit heat value plus a 10% extra cost to allow for additional investment at the service station to handle the increased volume.

In Table 3, all fuels are ranked on a cost-per-unit-energy basis as delivered at the fuel pump. Strip-mined shale is omitted because we believe that massive open-pit mining in western Colorado is not environmentally acceptable. There should be entries in the shaft-mined coal category, but we have not developed this topic on a comparable basis. However, we would expect the prices to be competitive with surface-mining methods when transportation to the eastern markets is included. Distillate runs about 10% cheaper than gasoline from the same resource.

From Table 3 we see that methanol is a competitive fuel. If engine efficiency is included, then methanol and gasoline from surface-mined coal have the same cost (on a dollars per kilometre basis) assuming the methanol engine is 17% more efficient than the gasoline engine. Additional efficiency improvements in the methanol engine would make methanol less expensive than gasoline (on a dollars per kilometre basis). In general, *in situ* processes will be cheaper provided they can be shown to be technically feasible.

Less developed alternatives include the production of methanol by various bioconversion methods. In such cases the basic energy source is solar, which has the desirable feature of being a renewable resource. Further work needs to be done on bioconversion processes, however, to determine their credibility.

Environmental Effects of Methanol

The nation should not accept widespread use of methanol without having carefully examined the environmental consequences. As industrial chemicals, methanol and gasoline have similar toxicity ratings. Methanol is highly toxic when ingested, while gasoline is highly toxic when inhaled. Since methanol is widely used as an industrial chemical, health and safety standards for handling it are already established. For general use, methanol should not be any more hazardous than is gasoline.

The manufacture of alternative fuels will have substantial environmental effects (unless *in situ* technology is developed). It will be necessary to reclaim strip-mined western coal lands (using a minimum amount of water); and it will be necessary to plan effectively for the influx of a large number of people into areas that are at present sparsely populated.

Prospects

A methanol-based transportation system may be a long-term solution to the nation's petroleum problem. More detailed information is needed to determine the full merits of this solution: in particular, how efficient and clean can a methanol engine be made? Nevertheless, current information indicates that methanol may be the best synthetic automotive fuel, and that a stratified-charge engine designed to run on methanol could offer superior fuel economy.

Key Words: alternate fuels; methanol; stratified-charge engine; synthesis gas; transportation.

ENVIRONMENT, HEALTH AND SAFETY

PHANTOM CONSTRUCTION: BUILDING A TORSO MANIKIN FOR WHOLE-BODY COUNTING

LLL's Hazards Control Department is constructing three plastic torso phantoms for ERDA's Division of Biological and Environmental Research. The phantoms will have removable major organs and are designed to simulate closely the geometry and tissue composition of human males; a series of removable chest plates simulates a wide range of sizes.

The phantoms are being built at the specific request of ERDA's Intercalibration Committee for Low-Energy Photon Measurements, established to standardize heavy-element whole-body counting techniques. Once completed, the phantoms will be dispersed to participating laboratories for use. The data gathered will then be compiled and exchanged to upgrade the calibration and counting techniques of all concerned laboratories.

The use of detectors to measure radioactive material deposited in the body is called whole-body counting. For plutonium and other heavy elements, counting is accomplished by placing sensitive detectors over the portion of the body closest to the organ being assayed and counting the radioactive emissions emanating from that organ (Fig. 8). Most transuranic isotopes decay by emission of alpha particles, characteristic x rays, and some low-energy gamma rays. But alpha particles are absorbed within a fraction of a millimetre in body tissue; only x rays and gamma rays can escape the body. Therefore, x-ray detectors, such as scintillation crystals or gas-filled proportional counters, are normally used for *in vivo* heavy-element counting.

Because of the low energy of its L-series x rays (17 keV) and its low x-ray yield (46 x-ray photons per 1000 alpha disintegrations), plutonium-239 is the most difficult transuranic isotope to measure sensitively and accurately in the body. Approximately half of these plutonium x rays are absorbed for each 6 mm of tissue penetrated, and almost another half are absorbed by the ribs. In the chest, less than 3 of the 46 x-ray photons per 1000 alpha disintegrations can penetrate the soft tissue overlying a male lung. But because the detectors only cover a portion of the

surface area, less than 10% of these three x-ray photons can be detected.

Even when plutonium is detected in the body, there are significant uncertainties about the geometric deposition pattern in any given organ and about the exact amount of tissue that reduces the number of x rays reaching the detector. These uncertainties make accurate assay of plutonium very difficult — a difficulty also found in measuring many other transuranic isotopes.

More than a dozen major laboratories are now involved in transuranic-isotope whole-body counting,⁸ which is one of the reasons that ERDA's Division of Biological and Environmental Research has established the Intercalibration Committee for Low-Energy Photon Measurements. The committee is staffed by experienced specialists from whole-body counting facilities at ERDA contractor laboratories and is responsible for calibrating heavy-element whole-body counting.

A major facet of this program is the design and construction of three human-torso phantoms. These phantoms, together with sets of organs loaded with plutonium-239 and other transuranic isotopes, will be sent to each participating laboratory for use, and the resulting data will be compiled and exchanged to upgrade the calibration and counting techniques of all participants.

The phantoms, now being built here, are based on general criteria provided by the Intercalibration Committee.⁹⁻¹¹ They will consist of the torso only with human-male rib cages and removable major organs, and will be made of materials simulating the low-energy x-ray transmission properties of human tissue. The tissues we need to simulate are muscle, adipose, cartilage, and lung. Each has significantly different transmission properties for low-energy x rays.

Each torso will have a wall thickness of about 15 mm to simulate tissue thickness in the chest and abdomen surrounding the internal organs; this thickness corresponds to the leanest individuals normally sent in for whole-body counting. Additional layers or chest plates will be made in 7-mm increments, growing to a maximum torso thickness of 43 mm; the composite phantom will therefore simulate a wide range of male statures.

Contact Richard V. Griffith (Ext. 3910) for further information on this article.

Fig. 8. In whole-body counting of transuranic isotopes, scintillation detectors are placed over the portion of the body closest to the organ being assayed and the x-ray photons emitted by the decay of the isotope are counted. Here, the detectors are positioned for an assay of the lungs.

Fig. 9. Here, a clear plastic shell replica of the torso is in place over the dark organ cavity mold and attached rib cage. With this arrangement, it is a simple task to measure and map tissue thickness of the torso wall — that region between the clear plastic shell and the cavity mold.

The removable organs include lungs, heart, liver, kidneys, and spleen. Because there is concern about deposition of transuranic isotopes in the lymph nodes, we will also include simplified sets of tracheobronchial lymph nodes loaded with radioactive material.

Torso and Organ Fabrication

Data from more than 500 males at the LLL and LASL whole-body counters show that the average individual assayed is 177 cm (5 ft 10 in.) tall, weighs 76 kg (169 lb), and has a chest circumference of 100 cm (39 in.). These dimensions were used to select the rib cages obtained through special arrangement with the anatomy department of a major medical center.

We made molds of the torso, organs, and organ cavity from the first cadaver rib cage donor. The organ cavity mold was made of a spongy material from which we made a plaster cast. We then vacuum-formed a clear plastic shell replica of the torso mold. This shell was positioned over the organ cavity mold and attached to the rib cage so that we could map the torso wall thickness (Fig. 9).

We obtained additional data on torso wall thickness from standard anatomy texts and ultrasonic measurements of several subjects. Based on this information and the mapping data, we fashioned a plaster torso model to a shape appropriate for the torso thickness of the basic "lean" phantom. A silicone mold was then made of this plaster model for casting the phantom (Fig. 10).

To complete the phantom, the rib cage will be affixed to a soluble cast of the organ cavity to form an inner mold. This mold will be suspended in position inside the silicone torso mold and the space between filled with tissue-equivalent plastic. The organ cavity replica will then be dissolved, leaving the rib cage imbedded in the torso casting, surrounding the organ cavity. The phantom torso with rib cage will then be ready for easy insertion of simulated organs into the organ cavity.

Preparing the rib cages requires mechanical removal of soft tissue, cleaning and solvent degreasing, and replacement of bone marrow with tissue-equivalent wax. The cleaning work was done at the Museum of Vertebrate Zoology, University of California, Berkeley. The museum maintains a colony of beetles (*Dermestes vulpinus*) to remove tissue from small animal skeletons; the colony was very useful in removing tissue from otherwise inaccessible parts of the rib cages. The bone marrow was replaced by submerging ribs and vertebrae

in molten tissue-equivalent Mix-D wax under vacuum, then bringing the chamber to ambient pressure, forcing the wax into the marrow channels. (Because Mix-D is hydrogenous, neutron radiographs are more effective than x rays in determining how well the bone has been penetrated; see Fig. 11.)

The rib cage reassembly was completed using nylon pins and string to reattach vertebrae and ribs. Cartilage-equivalent plastic segments will complete attachment of ribs to sternum, before we place them in the torso mold assembly.

Except for the lungs, all of the organ molds were cast directly from the original organs. Before casting, the lungs were reinflated and dried by maintaining a constant flow of air through the trachea. After 2 weeks, they had the texture of styrofoam and were then used to make plaster casts. We reshaped the lungs, liver, and heart somewhat to conform closely to the contour of the organ cavity before making the final molds and organ casts (Fig. 12). Blocks of tissue-equivalent plastic will be cast to fill space not occupied by major organs, space normally occupied by intestines, arteries, veins, and other soft-tissue structures that we are not concerned with.

Tissue-Equivalent Materials

Muscle or lean soft tissue represents the bulk of absorbing material in the human torso. We use tissue-equivalent material to simulate these soft tissues, and there is a variety available for different applications. Examples include specially formulated materials such as Mix-D wax, the depolymerized rubber Temex, and epoxy materials such as Rando muscle and lung simulants. But because we have special requirements, such as fabricating large and odd shapes with long-term shape retention and durability, it has been necessary for us to develop our own simulant mixtures.

With assistance from the Laboratory plastics shop, we have found that polyurethane is an excellent base for most of our tissue-equivalent needs. There are a number of commercial polyurethane materials available that can be used to simulate the soft tissues: muscle, adipose (fat), and cartilage. Foamed urethane materials can also be used to simulate 0.25-g/cm³ lung tissue. With a basic composition of about 65% carbon, 9% hydrogen, 5% nitrogen, and 21% oxygen, polyurethanes can be formulated to simulate the x-ray attenuation properties of tissue by adding small quantities of higher atomic number elements like calcium. The polyurethane is simple to handle and prepare.

Fig. 10. The final torso model, representing the leanest individual, and the silicone mold made from it. The soluble organ cavity mold with attached rib cage will be suspended in the torso mold and a tissue-equivalent mixture poured into the space between. The resulting cast will be a tissue equivalent torso with a rib cage embedded in it surrounding an organ cavity (the organ cavity mold dissolves).

Fig. 11. These neutron radiographs were used to determine how well the tissue-equivalent wax (Mix-D) penetrated the marrow and other soft-tissue regions of the ribs. (Top) An unaltered rib. (Bottom) A rib impregnated with Mix-D.

Fig. 12. A comparison of tissue-equivalent and real organs is shown here. We developed special polyurethane-based formulations for the tissue-equivalent mixture of each organ. (Top left) Liver. (Top right) Heart. (Bottom left) Lung with mold. (Bottom right) Kidneys.

Fig. 13. Comparison of the relative transmission of plutonium-238 L-series x rays through various tissue-equivalent materials. Polyurethane with 4.3% calcium carbonate (the LLL-developed mixture) and Mix-D are being used in our phantoms to simulate muscle and all other soft tissue, respectively. In the test set-up, the x-ray source was 80 mm from the detector, with each sample placed about 5 mm in front of the source.

We have measured the absorption of plutonium-238 x rays by various materials including beefsteak, water, and a number of tissue-equivalent materials. Our measurements show that the attenuation properties of water are sufficiently close to those of lean tissue that we will use water as a reference to formulate our muscle-equivalent material: the addition of 4.3% calcium carbonate is sufficient, using a commercial polyurethane, to achieve the necessary simulation (Fig. 13).

We will use muscle-equivalent tissue to simulate heart, liver, kidneys, spleen, and lymph nodes. Formulations for adipose and cartilage simulation are still under study.

The formulation for lung-equivalent material will be approximately the same, with the addition of about 4% calcium carbonate. Lung casting is somewhat more tedious than solid organs, however, because the material must be mixed and poured into the mold quickly so that polyurethane expansion takes place in the mold, not outside of it. Foaming the polyurethane is critically dependent on water quantity; and because small amounts of water are used, accurate formulation is important to achieving the proper density.

An additional requirement in organ fabrication, particularly for the lungs, is the ability to include transuranic isotopes uniformly mixed throughout the organ volume. We now feel this loading can be done by dissolving the transuranic nitrate in acetone using

lanthanum nitrate as the carrier. More than 3 cm³ of 10% lanthanum-acetone solution can be added to a 500-g lung section without affecting the foaming process. X-ray fluorescence analysis of samples from lungs loaded in this way shows very uniform distribution of the lanthanum. We fully expect to be able to load solid organs such as the liver in the same way.

Future Plans

The first phantom, with one loaded lung set, is scheduled to be finished in March 1977; all three phantoms are to be finished by October. The first phantom will be sent to the laboratories represented by members on the Intercalibration Committee for evaluation. In addition to the initial lung set, there will be lungs, lymph nodes, and livers loaded with plutonium-238, plutonium-239, americium-241, and uranium-235. After evaluation, all three phantoms will be sent to U.S. laboratories having major heavy-element whole-body counting programs, and the results will provide data for the first phantom intercomparison program. At that point, use of the phantoms will be dictated by the results and the needs of the radiation protection community.

Key Words: dummies; manikins; phantoms; radiation counters; radiation phantoms; whole body counters.

ADVANCED ENERGY SYSTEMS

NATIONAL MFE COMPUTER CENTER: 1976 UPDATE

The national magnetic-fusion-energy (MFE) computer center at Livermore, operational since the fall of 1974, expanded its data communication network and improved its software and hardware during 1976. The network now includes seven user service centers across the country (including two at LLL) connected by 50 000-bit/s transmission lines to the MFE center. The most recent addition is a service center at Science Applications, Inc. in La Jolla, California. Among the major developments this past year is a high-speed channel that standardizes the process of interfacing computers of various manufacturers. FILEM, a versatile file-management system for remote users, was also significantly improved and will include a 500-billion-bit mass storage facility later this year. Demand for computational support in the MFE community continues to outstrip the center's capacity, requiring us to plan for a second CDC 7600 at Livermore and spurring interest in a next-generation computer as a third processing unit.

In 1974, LLL was selected as the site for a national magnetic-fusion-energy computer center (MFECC). Computational studies at the center were to be keyed to the research needs of the three principal MFE confinement schemes: low-density closed systems (mainly tokamaks), high- β systems (mainly the theta pinch), and open systems (magnetic mirrors). Major MFE research sites and scientists at universities with ERDA-sponsored MFE projects were to have access to the national center.

In the fall of 1974, the center went online to users via voice-grade telephone lines with a CDC 6600 as the central computer and a remote job entry terminal at the Princeton Plasma Physics Laboratory. One year later, a CDC 7600 replaced the 6600, inaugurating large-scale computational support to the MFE community. High-speed (50 000-bit/s) transmission lines were operational by mid-1976 to four user service centers: Los Alamos Scientific Laboratory, Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory, and General Atomic Co., San Diego, California. The advent of these transmission lines

marked the start of a national wideband communications network.

The idea behind a national MFE computer center is to provide large-scale computer capability in addition to local capability at various remote locations according to research priorities and anticipated computational demand. The CDC 7600 central computer, available to the entire MFE community, has 64 000 words of small semiconductor memory, 500 000 words of large-core memory, and disk storage. The national center also has a PDP-11/50 central communications control processor, a PDP-11/50 network control station, and a CDC 6400 file management computer that stores files and maintains indices for information retrieval.

The user service centers have PDP-10 computers systems with direct high-speed access to the national center through PDP-11/40 remote communications control processors. Seven service centers are now operational: one for the MFE program at LLL, one at the MFE computer center, and one each at Princeton, Oak Ridge, LASL, General Atomic, and Science Applications Inc. (SAI), La Jolla, California. The SAI service center, our latest addition, is connected to the 50 000-bit/s transmission line that terminates at General Atomic.

Small computation problems are handled locally at the user service centers. Large-scale problems are routed to the national center and then returned to the service centers for final processing. For offnet users, the ultimate intent is to provide either mini-service centers or remote job entry terminals. Access for these users to the national center is currently via leased telephone lines. Figure 14 shows the present configuration of the MFE computer network.

1976 Update

At the time of our initial article on the computer center in December 1975,¹² user access to the CDC 7600 was via dial-up voice-grade lines, and the 50 000-bit/s lines were in the process of being installed and checked out. Even at this early stage it was evident that the forecasts of MFE demand for large-scale computing were not exaggerated. With the help of the center's programming staff, users quickly converted their codes for operation on the national system, and

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Fig. 14. General arrangement and connections between user service centers and the national MFE computer center (MFECC). The network includes seven user service centers: two at LLL (one for the MFE program and one at the computer center), and one each at Los Alamos Scientific Laboratory (LASL), Princeton Plasma Physics Laboratory (PPPL), Oak Ridge National Laboratory (ORNL), General Atomic (GA), and Science Applications Inc. (SAI). Princeton also has a remote job entry terminal (RJET). A 32-line autoanswer modem (shown at upper right) provides offnet users with voice-grade dial-up access to the central computer facilities. All unshaded equipment is part of the central computing facility at Livermore.

the capacity of the 7600-A machine was saturated early in 1976.

During this past year, we have concentrated on software and hardware refinements of the central computing system at Livermore and on developing improved user access via the data communication network.

Software and Hardware. In February, the capability of the CDC 7600 was enhanced by installing four high-performance CDC 819 disk drives and associated controllers. Software and hardware integration of these units into the system was accomplished to permit their use in early March.

Another need recognized early by the center's staff was a standardized high-speed channel (10 to 40 million bits/s) to be used for interprocessor communication. A large computer center needs to interconnect many varieties of computers of different manufacturers and models. Interconnecting channels

are sometimes available between models of the same manufacturer but rarely between competitors' models, such as a CDC 6400 and a DEC PDP-11. At best, one would end up with a large array of interconnecting channels, each unique and incompatible with the others, with special designs required when no channel was available. Standardization would replace this with channels that allow total freedom of choice of interconnected computer pairs and could be structured to minimize custom hardware and software design.

A computer standard interface channel for computer intercommunication has been designed. Interfaces currently nearing completion include those for a CDC 7600, CDC 6400, DEC PDP-10, and DEC PDP-11. The interface channels will connect any of these machines to any other. Additionally, an interface to an HP 2100 minicomputer has been designed to allow connection to the LLL M-Division PDP-10, which will also have the standard channel interface.

Data Communication Network. The ability to move files (first alpha-numeric, next graphic, and then binary) from the CDC 7600 to our user service centers through the 50 000-bit/s transmission lines was accomplished in March and April. In May we inaugurated input file traffic from the service centers to the 7600, and in July we implemented file traffic between service centers. Interactive terminal traffic over the transmission line became operational in September. Interactive terminal access for nearly all sites not served by a user service center has remained available via autoanswer modem, which handles 28 dial-up users at 300 bits/s and 4 users at 1200 bits/s.

Development continued this past year on FILEM, a highly versatile file-management system that allows remote users to store and retrieve programs and data files at Livermore for an indefinite time. FILEM was designed to accommodate the special needs of users at remote sites, and the system has enjoyed excellent customer acceptance (Fig. 15). To enhance the FILEM system, we also selected a 500-billion-bit mass storage facility — Control Data model 38500 — which was approved by ERDA in August; estimated delivery of the storage facility is December 1977.

Currently FILEM uses rotating storage (CDC 844 disk packs) for medium-term file storage. When the mass storage facility is online, a file to be stored will be transferred to the facility with a copy also written onto the FILEM disk system for short-term rapid access. The urgent need for such a system has required the computer center to temporarily simulate the mass storage facility by transferring the data onto

Fig. 15. Growth in user demand for central file storage in FILEM, a versatile file-management system enabling remote users to store and retrieve programs and files at the MFE computer center.

Fig. 16. Projected demand and anticipated hardware needed to keep pace with that demand at the MFE computer center. Projected demand comes from a 1976 survey in which users were asked to estimate their requirements by fiscal years. Immediate plans call for adding another CDC 7600 in 1977. We are also studying the possibility of adding a class VI (next-generation) computer as a third central processing unit in 1978.

conventional magnetic tape. However, these tapes must be manually retrieved, mounted, demounted, indexed, and stored.

A FILEM software effort under way during the past year has been programming the CDC 6400 to assume virtually all of the tasks associated with file custodianship, including indexing, storage, retrieval, and efficient management and allocation of the file storage media.

Future Growth

The immediate problem facing the MFE computer center is that the ever-increasing demand for more computing time has oversubscribed the capacity of a single 7600. We need at least one more 7600 and are also planning to add a class VI (next-generation) processor as a third major central processing unit in FY 1978. As an interim stop-gap measure, the center is currently acquiring blocks of computer time from

the 7600 at the Lawrence Berkeley Laboratory for MFE users. Figure 16 shows anticipated future computational demand for the computer center.

A related development this year was establishing the design criteria and selecting an architect-engineering firm for our new \$5 million computer facility. Construction is scheduled to begin in October 1977;

complete occupancy is slated for December 1978. The 3700-m² facility is designed to accommodate three major computing mainframes and offices for about 87 people, including center staff and visitors.

Key Words: fusion research; MFECC; magnetic fusion energy.

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