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About the Cover

The Veil Nebula, a supernova remnant (photograph courtesy of the Hale Observatory). Current theory holds that the universe began with a Big Bang and the galaxies formed shortly thereafter. The age of our solar system is known well, but the age of our galaxy, the Milky Way, is not. However, the heavier elements in the Milky Way originated in supernovae such as the one that produced the Veil. Therefore, we may estimate the age of the universe by determining the duration of nucleosynthesis, i.e., the length of the period during which the matter of which our solar system is composed was being processed in the stars. This determination is provided by nuclear-dating techniques based upon the knowledge of the relative isotopic abundances and the decay rates of the nuclear species used in dating. However, the use of such a technique depends critically upon the knowledge of the cross section for the neutron-capture reactions which create and destroy these key nuclear species in a stellar environment. For information about a new measurement of the key cross sections which are necessary for determining the age of the universe, see the article beginning on p. 1.

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About the Journal

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How Old is the Universe?

Our measurement of the neutron-capture cross sections for two rare isotopes of osmium provides the data necessary for a new radiogenic determination of the age of the universe.

1

Measuring Equations of State with the Electric Gun

We have demonstrated that the electric gun can generate shock pressures near 1 TPa in tantalum.

11

The Feasibility of Inertial-Confinement Fusion

John Nuckolls, in his Maxwell Prize Address, cites recent encouraging experiments that demonstrate the efficient coupling of laser light to targets and describes new ideas for economically competitive power plants.

18

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of the chronometer nuclei depends upon the assumption, which is hard to test, that each of the progenitors of the chronometer nuclei was present in equal abundance. Second, the half-lives of the chronometer nuclei are comparable to (and not much longer than) their age; any uncertainties in their determination thus multiply exponentially.

In contrast to the *r* process, the *s* process rests upon a firmer theoretical footing, as we will show below. We have used a model based upon the *s* process to make a new determination of the age of the universe.

The Rhenium-Osmium Clock

About twenty years ago, it was suggested by Clayton⁷ that the uncertainty in the radiogenic age determination of the universe might be reduced by using as a nuclear chronometer an *s*-process nucleus. The stable light isotopes of the heavy metal osmium—osmium-186 and osmium-187—are pure *s*-process nuclei (being shielded from the *r* process by stable tungsten-186 and long-lived rhenium-187, respectively) and are found in a relatively undisturbed state in primordial meteorites. Further, osmium-187 can result from the beta decay of rhenium-187, which has a half-life of about 43 b.y., far longer than the age of the universe (see Fig. 2 inset).

An *s*-process chronometer does depend, however, on the validity of the "local" assumption that the product $N\bar{\sigma}$ is constant for adjacent *s*-process nuclei, where N is the *s*-process equilibrium abundance of a given nuclear species and $\bar{\sigma}$ is the Maxwellian-averaged neutron-capture cross section of that species at the temperature T appropriate to the stellar site of the *s* process (commonly accepted as kT equal to about 30 keV, where k is the universal gas constant). This assumption is well supported for the isotopes of strontium, zirconium, tin, and samarium.⁸ Because this assumption is likely to hold even more rigorously for the isotopes of osmium, which are far from any nuclear shell closure, little uncertainty should result from its use.

The determination of the duration of nucleosynthesis Δ requires several steps (see box on p. 4). We wish to establish the original *s*-process abundance of osmium-187. Because a portion of the osmium-187 originated by beta decay from the *r*-process nucleus rhenium-187, we have to find the ratio R of the abundance of the radiogenically produced osmium-187 to that of its parent nucleus, rhenium-187 (see Eq. (2) in box).

The isotopic abundance ratios pertinent to the determination of the value of R are obtained from meteoritic data (which are uncertain to $\pm 10\%$).⁹ But the creation and destruction rates of osmium-187 in a stellar neutron flux are determined by the relative neutron-capture cross sections for osmium-186 and osmium-187. Therefore, in order to determine Δ , we had to measure the ratio of the neutron-capture cross sections ($\sigma_{186}/\sigma_{187}$).

The value of the latter ratio then must be multiplied by a correction factor f to account for the fact that osmium-187 nuclei in a stellar environment exist in a low-lying excited state (at about 10 keV) as well as in their ground state. (Osmium-186 and rhenium-187 do not have any excited states below 100 keV.) We use the measured value of $\sigma_{186}/\sigma_{187}$ and a calculated value of f to obtain R . We then determine Δ from R using Eq. (3) in the box.

Finally, the value of Δ also depends upon the supernova rate in the galaxy λ_A (see box). We used three alternative models to estimate λ_A : a uniform rate, an exponentially decreasing rate, and a single event.

Measurement of the Neutron-Capture Cross Sections

The key to our determination of the age of the universe was the measurement of the ratio of the neutron-capture cross sections for osmium-186 and osmium-187.¹⁰ This measurement required sufficiently massive and highly purified samples of these two rare isotopes. The measurements were carried out at LLNL; the samples, produced by a one-and-a-half-year effort at the Oak

The Determination of Δ Using the Rhenium-Osmium Clock

The rhenium-osmium clock depends upon the following principle. If we consider what the nuclear abundances were at the time of solar-system condensation (i.e., just after Δ , the period of nucleosynthesis), then the amount of osmium-187 that was produced by beta decay of rhenium-187 depends upon Δ . The amount of rhenium-187 produced by nucleosynthesis also depends upon Δ . Hence, if we can determine the ratio R of the amount of the daughter nucleus osmium-187 produced by beta decay to the amount of its parent rhenium-187, we then can extract a value of Δ . In doing this, we must account for the fact that osmium-187 also was produced and destroyed by the s process during nucleosynthesis.

If the s-process abundances of osmium-186 and osmium-187 are denoted by N_{Os}^{186} and N_{Os}^{187} , respectively, and the radiogenic component of osmium-187 resulting from beta decay of rhenium-187 by N_{rad}^{187} , the total abundances of osmium-186 (N^{186}) and osmium-187 (N^{187}) are

$$N^{186} = N_{\text{Os}}^{186}$$

and

$$N^{187} = N_{\text{Os}}^{187} + N_{\text{rad}}^{187} \quad (1)$$

Using the local assumption that $N_{\text{Os}}^{186} \bar{\sigma}_{186} = N_{\text{Os}}^{187} \bar{\sigma}_{187}$, where $\bar{\sigma}_{186}$ and $\bar{\sigma}_{187}$ are the Maxwellian-averaged neutron-capture cross sections for osmium-186 and osmium-187, respectively, together with Eq. (1), we then can express the ratio of N_{rad}^{187} to its parent rhenium-187 abundance N_{Re}^{187} as

$$R = \frac{N_{\text{rad}}^{187}}{N_{\text{Re}}^{187}} = \frac{(N^{187}/N_{\text{Os}}) - f(\bar{\sigma}_{186}/\bar{\sigma}_{187})(N^{186}/N_{\text{Os}})}{N_{\text{Re}}^{187}/N_{\text{Re}}} \times \frac{N_{\text{Os}}}{N_{\text{Re}}} \quad (2)$$

where N_{Os} and N_{Re} are the elemental abundances of osmium and rhenium. This value of R is for the time of solar system condensation, with all the isotopic abundances evaluated at that time. (The cross-section ratio $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ measured in the laboratory must be multiplied by a correction factor f to account for the fact that in a stellar environment osmium-187 nuclei exist in both ground and excited states).

If we assume that the r-process nucleosynthesis that produced rhenium-187 began at a time Δ before the condensation of the solar system and decreased exponentially, the rate of decrease λ_A is a measure of the supernova rate in the galaxy. If λ_B is the beta-decay rate of rhenium-187, we then can use the Bateman equations for radioactive growth and decay to express the ratio R at the time of solar-system condensation as

$$R = \frac{N_{\text{rad}}^{187}}{N_{\text{Re}}^{187}} = \left\{ \frac{\lambda_A - \lambda_B}{\lambda_A} \exp(\lambda_B \Delta) \times \frac{1 - \exp(-\lambda_A \Delta)}{1 - \exp[-(\lambda_A - \lambda_B) \Delta]} \right\} - 1 \quad (3)$$

This model has two extreme cases: (1) sudden synthesis, a single supernova event for which λ_A approaches infinity and the value of R in Eq. (3) becomes approximately equal to $\lambda_B \Delta$ ($\lambda_B \Delta$ is much smaller than unity), and (2) uniform synthesis, for which λ_A approaches zero and R becomes approximately equal to $\lambda_B \Delta/2$. We have chosen a "happy medium" value for λ_A , assuming that the supernova rate was higher when the galaxy was younger. This assumption corresponds to the early existence of a larger number of massive stars than now; such stars are more likely to end their existence as supernovae, and to do so more quickly, than less massive stars. We have used a value of 0.43 for λ_A^{-1} . (This value has also been used to determine Δ by the uranium-thorium method).*

We obtained the isotopic abundance ratios in Eq. (2) using data from meteorites and a rhenium-187 half-life of 43 by. Extrapolated back to the time the solar system condensed, these data give a value of 0.0125 ± 0.0006 for $N_{\text{rad}}^{187}/N_{\text{Os}}$, 0.0159 for $N_{\text{Os}}^{186}/N_{\text{Os}}$, and 0.65 for $N_{\text{Re}}^{187}/N_{\text{Re}}$. (The geochemical uncertainties for the last two quantities are negligible.) For the elemental abundance ratio $N_{\text{Os}}/N_{\text{Re}}$, we used the value 13.1 ± 0.6 , obtained from an analysis of C1 carbonaceous chondrites only.[†] This value excludes the slightly lower values obtained from other types of meteorites that are thought to be less ancient.

The remaining quantities critical to the determination of Δ are the measured cross-section ratio $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ and its correction factor f .

*W. A. Fowler, in *Cosmology, Fusion, and Other Matters* (Ed., F. Reines), Colorado Assoc. Univ. Press, Boulder, Colorado (1972).

[†]S. E. Woosley, private communication (1979).

Ridge National Laboratory (ORNL), consisted of 3.278 g of 78.39% isotopically pure osmium-186 and 2.959 g of 70.96% isotopically pure osmium-187.

Our experiment was performed at the neutron time-of-flight facility at the LLNL Electron-Positron Linear Accelerator. Figure 3 is a schematic diagram of the experimental apparatus. The experiment consisted of irradiating the isotopic samples with neutrons and detecting the gamma rays emitted by the neutron-capture process. Neutrons were produced by irradiating a water-cooled tantalum target with a pulsed 115-MeV electron beam from the accelerator. The

neutron energies were determined by their flight times down an evacuated, 15-m-long collimated tube to the samples (see Fig. 3). The energy profile of the neutron flux was measured by scattering the neutrons from a thin graphite foil located on an adjacent flight path into a nearby lithium-6 glass scintillation detector. This detector also served as a neutron monitor for cycling the osmium samples.

The samples were enclosed in lightweight beryllium containers. (Because the samples were not 100% pure, the other osmium isotopes present were measured as well.) We used a pair of

Fig. 3

Schematic diagram of the neutron-capture cross-section experiment. (a) Neutrons were produced in a water-cooled tantalum target struck by a pulsed 115-MeV electron beam from the LLNL Electron-Positron Linear Accelerator. (b) The osmium samples were cycled into position in the collimated neutron beam between two deuterated-benzene (C₆D₆) scintillation detectors that measured the gamma rays emitted by neutron capture. (c) The neutron flux was monitored on a separate flight path with a lithium-6 glass scintillator. (Figure adapted from Ref. 10.)

Fig. 4

Average neutron-capture cross sections for osmium-186 and osmium-187 as a function of neutron energy, as measured with the apparatus shown in Fig. 3. From these data, the Maxwellian-averaged cross sections for a kT of 30 keV were obtained; their ratio is a necessary parameter for determining the ratio of the s -process abundance of osmium-187 to the radiogenic component of osmium-187 resulting from the beta decay of rhenium-187. (Figure adapted from Ref. 10.)

one-litre deuterated-benzene liquid scintillators to detect the neutron-capture gamma rays. (Deuterated material was used to eliminate the severe background that would have resulted from the 2.2-MeV gamma rays produced when neutrons are captured by ordinary hydrogen.) They were positioned close to the sample in order to subtend a large solid angle.

Figure 4 shows the neutron-capture cross sections of osmium-186 and osmium-187 measured in our experiment. Using these data, we obtained the Maxwellian-averaged cross sections for kT equal to 30 keV, the temperature appropriate to the stellar site of the s process. The value of the resulting ratio $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ was 0.48 ± 0.04 . (Similar measurements were subsequently made at the National Bureau of Standards at 25 keV using an iron-filtered neutron beam from a reactor¹¹ and at the electron linear accelerator at ORNL, another neutron time-of-flight measure-

ment.¹² These experiments gave values for $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ of 0.475 ± 0.075 and 0.478 ± 0.022 , respectively.) Thus, all three results are in excellent agreement.

We next applied the correction factor f to account for excited nuclear states in the stellar interior. This calculation requires as input parameters (among other things) the level spacings and spin distributions in the nuclei of osmium-187 and osmium-188, which result from neutron capture by osmium-186 and osmium-187, respectively.¹³ Some of the input data for this calculation came from another LLNL linac experiment.¹⁴ Figure 5 shows the curve representing f as a function of temperature. The value of f at kT equal to 30 keV (3.6×10^8 degrees) is 0.83. (This parameter does not depend strongly upon temperature for values reasonably near 30 keV).

The Duration of Nucleosynthesis

We next related the measured value of $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ to a value for Δ , the duration of nucleosynthesis, using equations (2) and (3) in the box on p. 4. Figure 6 shows the results corresponding to the three models for the supernova rate in our galaxy.¹⁵ The available experimental data for $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ were combined to give a value of 0.478 ± 0.018 (shown as the data point on the middle curve of Fig. 6), which corresponds to a value for Δ of 10.8 ± 1.2 b.y.

However, because of uncertainties in the value of f and in the half-life of rhenium-187 (which have not yet been included), we must increase the uncertainty in Δ . The uncertainty in f results from a discrepancy between two recent experimental determinations of the inelastic neutron-scattering cross section for osmium-187.¹⁶ The effect of the measurements is in one case to suggest an increase and in the other a decrease in the value of f used here, each by about 20%. Resolution of this uncertainty awaits a better measurement of the inelastic neutron-scattering cross section of osmium-187 at 30 keV.

Because it is very difficult to measure accurately, the half-life of rhenium-187 is also in some doubt. There is an effort

underway at LLNL¹⁷ to measure an accurate value for the half-life of rhenium-187 using nuclear-chemistry techniques. Because the beta-decay energy of rhenium-187 is very low (2.6 keV), the half-life will be determined indirectly by measuring the number of daughter osmium-187 atoms produced from the decay of rhenium-187. So far, five 1-kg batches of absolutely osmium-free perrhenic acid solution have been produced from which will be extracted the approximately 10^{13} atoms of the radiogenic daughter osmium-187 atoms which grow into each batch during a one-year period. This measurement necessitated the development of an entirely novel method of chemical separation, because the final product—osmium-187—must contain less than one atom of rhenium-187 in approximately 100 atoms of osmium-187 for the results to be significant, although the initial ratio was 10^{12} atoms of rhenium-187 for each atom of osmium-187. With the help of scientists at the National Bureau of Standards, a laser-microprobe mass analyzer will be used for the mass spectrometry of very small samples (i.e., less than a nanogram) of osmium.

A few other potential problems might be associated with the use of the rhenium-osmium clock. For example, the high temperatures and densities prevailing in a stellar interior might affect the rhenium-to-osmium beta-decay rate. The temperature effect would shorten, and the density effect lengthen, the half-life of rhenium-187. There is also an isomeric state of rhenium-186 (with a half-life of 2×10^5 years) that could short-circuit the s process to some extent, resulting in the production of some s-process rhenium-187.¹⁸ Finally, the value of the elemental abundance ratio of osmium to rhenium remains somewhat controversial. None of these qualifications, however, appears at this time to jeopardize our analysis seriously.

Incorporating reasonable uncertainties for the correction factor f and for the half-life of rhenium-187 into the uncertainty in our value for Δ , we obtain a "best" value of 10.8 ± 2.2 b.y.

Fig. 5

The correction factor f relates the ratio of the measured Maxwellian-averaged neutron-capture cross sections for osmium-186 and osmium-187 to the appropriate stellar conditions. For a temperature near 3.6×10^8 degrees ($kT = 30$ keV), typical of stellar conditions, the value of f is about 0.83.

The largest part of our uncertainty is associated with the determination of f . This result is significantly larger than the value of 6.1 ± 2.3 b.y. obtained with the r-process uranium-thorium method.

The Age of the Universe

Adding our value of Δ (10.8 ± 2.2 b.y.) to the age of the solar system (4.7 ± 0.1 b.y.) gives us an age for the galaxy of 15.5 ± 2.3 b.y. This number is concordant, but not comfortably so, with the value of 11 ± 3 b.y. obtained with the globular-cluster method.¹⁹ (This method attempts to date globular clusters, perhaps the oldest objects in our galaxy. Using the ratio of helium to hydrogen obtained from observations of the visible light from stars in these clusters, one can calculate the age of the galaxy from stellar models. This method depends upon assumptions

Fig. 6

The duration of nucleosynthesis Δ before the condensation of the solar system as a function of the ratio of the measured Maxwellian-averaged neutron-capture cross sections for osmium-186 and osmium-187. The supernova rate λ_A is represented by three alternative models: a uniform rate ($\lambda_A = 0$), an exponentially decreasing rate $\lambda_A = (0.43\Delta)^{-1}$, and a single event ($\lambda_A = \infty$). The data point represents the combined results of several measurements, including the one done at LLNL. The error bar includes the experimental uncertainties, but not those resulting from the values used for the half-life of rhenium-187 or for the correction factor f .

about stellar evolution and the primordial helium abundance, and is thus somewhat uncertain.) Far more encouraging are the recently reported spectral and photometric observations of two faint galaxies whose ages are estimated at between 15 and 18 b.y., making them the oldest objects observed to date.²⁰

Finally, adding 1.5 ± 0.5 b.y. to account for the time between the Big Bang and the formation of the galaxy gives us a value of 17 ± 2.5 b.y. for A_U , the age of the universe. To take account of additional uncertainties that cannot be explicitly evaluated at present, this uncertainty probably should be increased to ± 3 b.y.

Implications for Cosmology

If we assume the validity of Hubble's law, namely, that the greater the distance of an astronomical object the farther its radiation spectrum is shifted to longer wavelengths, then the observation of such objects indicates that the universe is expanding. The constant of proportionality in this relationship is called the Hubble constant, and its inverse the Hubble time T_H . If the universe had been expanding at a constant rate since its origin, T_H would equal the age of the universe. In other words, if Hubble's law is valid, T_H represents an upper limit for A_U . (It would equal A_U if the universe were not being decelerated by the mutual gravitational attraction of the matter it contains.) The most recent conventional value for T_H is 16.6 ± 1.7 b.y.²¹ This value (nearly the same as our value for A_U) implies

that little or no deceleration has occurred, which in turn implies that the universe is open and will expand forever (see the rust line in Fig. 7).

If the value of T_H were much larger than that of A_U , the universe would be sufficiently massive to be closed, eventually contracting upon itself, and finally ending its existence in a "Big Crunch," an event that may be thought of as a time-reversed version of the Big Bang (see the green line in Fig. 7). The near equality of T_H and A_U , in contrast, suggests that the universe will end "not with a bang but a whimper."

These arguments are based upon a model of the universe in which conventional ideas about gravitation hold, corresponding to a null value for the cosmological constant in Einstein's equations of general relativity. Recent evidence, however, suggests that T_H may be only about 10 b.y.,²² substantially smaller than the value of A_U that we have determined. This new value of T_H then would imply that at sufficiently large distances, objects in the universe are subject to a mutual repulsion, corresponding to a positive value of Einstein's cosmological constant (as represented by the gold line in Fig. 7). If substantiated, this result would be of supreme importance to cosmology, because the only alternative to mutual repulsion would be a

Fig. 7

Three scenarios for the evolution of the scale of the universe over time, for various values of the Hubble time T_H relative to the age of the universe A_U . The scenarios assume the validity of the Big Bang theory of the origin of the universe. The rust line, for T_H only slightly greater than A_U , represents an open universe that expands forever at a gradually decreasing rate. The green line, for T_H much greater than A_U , represents a closed universe that eventually contracts upon itself. The gold line, for T_H less than A_U , represents the possible evolution of a universe in which Einstein's cosmological constant is greater than zero, corresponding to a mutual repulsion of the objects in the universe at sufficiently large distances.

universe whose early history cannot be described by the Big-Bang model. Although few astrophysicists currently subscribe to either of these possibilities, they represent an exciting challenge that can be resolved only with further evidence.

Summary

We have made a new determination of the age of the universe based upon the use of the rhenium-osmium beta-decay clock. The crucial experimental element in this determination was our measurement of the neutron-capture cross sections for osmium-186 and osmium-187, in the energy range corresponding to stellar temperatures. The use of this clock gives us a value for the time elapsed between the formation of the Milky Way and the condensation of the solar system, the period during which the present matter of the solar system was undergoing nucleosynthesis in the interior of stars. Including reasonable assumptions and incorporating appropriate uncertainties, our determination of the age of the universe is 17 ± 3 billion years. This value, although significantly larger than the results of previous determinations, agrees with the age of recently discovered galaxies. It is greater, however, than the apparent limit set by the most recent determination of the Hubble time. This difference has implications of crucial significance for cosmology. $\square$

Key Words: age of universe; Big Bang; Hubble time; LLNL linear accelerator (linac); nucleosynthesis; neutron-capture cross section; osmium; radiogenic dating; rhenium-osmium clock; r process; s process; supernova.

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ELECTRIC GUN

Fig. 1

Exploded and partial cutaway view of a typical electric-gun configuration for an EOS experiment. The impactor (projectile)—usually a thin foil or a composite of several foils—is accelerated to a high velocity when an adjacent metal foil is electrically exploded by rapid Joule heating. When the foil explodes, it punches out a section of the impactor and drives it up the evacuated barrel to strike the target. The transmission line, impactor, barrel, and target are fastened together in a stiff assembly that is placed in an experimental chamber and attached to a capacitor bank so that current can pass through the transmission line.

To understand the behavior of a material subjected to extremely high pressures, such as those produced during a nuclear explosion, it is necessary to know its equation of state (EOS) in the appropriate pressure range. The EOS of a material can be studied in the laboratory by shock waves generated by various devices. The highest laboratory pressure achievable in uranium with current two-stage gas guns is about 500 GPa. To verify the EOS parameters used in our nuclear design codes, however, we must be able to generate pressures of 1 TPa and above. One very promising technology we have explored to extend the range of EOS determinations is the electric gun.¹

In an electric gun, an impactor (projectile)—usually a thin foil or a composite of several foils—is accelerated to a high velocity when an adjacent metal foil is electrically exploded by rapid Joule heating (Fig. 1). When

the foil explodes, it punches out a section of the impactor and drives it up an evacuated barrel to strike the target.

The energy density achievable in the exploding foil is many times that obtained with chemical high explosives. Moreover, intense magnetic fields generated by the currents flowing in the foil plasma and rear conductor impart a substantial additional acceleration (Lorenz acceleration) to the impactor. As a result, the projectile may be accelerated to velocities well beyond the reach of other technologies. The fastest electric-gun system in use at LLNL has accelerated plastic projectiles 0.3 mm thick and 8 mm in diameter to a velocity of 30 km/s. This capability led us to explore the electric gun's potential as a shock-wave generator in experiments designed to characterize the EOS of a material at high pressures.

Apart from its electrical power source, the electric gun is an inexpensive, throw-away device that dissipates

a relatively small amount of energy compared to gas guns or high-explosive systems. Because it is self-contained, it is especially suited to experiments on hazardous materials that might otherwise contaminate an expensive and complex research facility.

Although the electric gun is conceptually simple, a number of difficulties arise in applying it to EOS experiments. A substantial part of our research has been aimed at identifying and solving such problems as hydrodynamic jetting, target preheat and premotion, impactor preheat and nonplanarity. We have also developed experimental and diagnostic techniques with accuracies in the range of 1 to 2%.

We chose tantalum as the test material in these proof-of-concept experiments because its EOS already has been well characterized by other means. Our experiments with tantalum were designed for symmetric impact; that is, both the impactor and the target were made of tantalum. Symmetry considerations show that at the instant of impact, the resulting material velocity in the shocked target U_T is exactly one-half the velocity of the impactor (Fig. 2). By measuring the velocity of the impactor V_i and the shock velocity in the target U_S , we can use the Rankine-Hugoniot relations to derive values of pressure, volume, and energy in the shocked material (see box below).

Fig. 2

Schematic of an impactor collision with a stepped target just after impact (a). In region 3, the material is still moving at the velocity of the impactor V_i with normal density ρ_0 and zero pressure compared to the shocked state. At the boundary between regions 2 and 3, the material abruptly slows to the material velocity U_T (which is exactly one half of V_i if the target and impactor are of the same material), and is compressed to a density ρ and a pressure P . In region 1, the material is at rest with density ρ_0 and zero pressure. Leftward- and rightward-moving shock waves (shaded bands) are driven into regions 1 and 3, respectively. The leftward-moving shock wave (at the boundary between regions 1 and 2) moves into region 1 with a shock velocity U_S , while the rightward-moving shock wave moves into region 3 with velocity $U_S - V_i$ (in the laboratory's frame of reference). In (b), the shock wave has broken out on the lower part of the step, and the rarefaction-affected zone is beginning to form. In (c), the shock has reached the lower edge of the step, and the rarefaction-affected zone is fully developed.

The experimental parameters measured are the impactor velocity V_i (and thus the material velocity U_T) and the shock velocity U_S . We measure the shock velocity by recording the time interval between the shock's arrival at the lower and upper parts of the step at points outside the rarefaction-affected zone.

Deriving the Equation of State

Conservation of mass, momentum, and energy for a steady shock wave leads to the Rankine-Hugoniot equations,

$$\rho_0 U_S = \rho (U_S - U_T),$$

$$P = \rho_0 U_S U_T,$$

$$e - e_0 = P(v_0 - v)/2,$$

where $v_0 = 1/\rho_0$, $v = 1/\rho$, and e and e_0 are specific internal energies of the shocked and unshocked states, respectively (regions 2 and 1 in Fig. 2); we have neglected the

initial pressure in the unshocked region. We use Eqs. (1) and (2) to calculate the P and ρ that correspond to the U_T and U_S measured experimentally. The loci of points corresponding to shocked states are called Hugoniot curves. The (P, ρ) Hugoniot curve, for example, is the locus of (P, ρ) points that can be generated in a single shock and corresponds to a single line on the EOS surface $e = e(P, \rho)$.

To generate an EOS from shock-wave data, we must make an additional assumption regarding the form of $e(P, \rho)$. The shock-wave data, plus additional thermodynamic data from other experiments, are used to calibrate the EOS model.

Fig. 3

Streak-camera record of the impact of a 30- μm -thick tantalum foil, traveling at 7.4 km/s, on a flat glass (left) and tantalum (right) target. The record on the glass side shows that the impactor is smooth to within 2 μm and quite flat. The right side shows the shock breakout in the tantalum target step, from which we can measure the shock velocity U_s (see Fig. 2). There is some curvature apparent on the tantalum target side. Because of the small step height, this amount of curvature introduces only a negligible error into the determination of U_s . The train of light spots down the left side of the record are pulses from an accurately calibrated, mode-locked laser.

Design of the Electric-Gun EOS Experiments

We used two different impactor designs. In the lower-velocity experiments, the design consisted of a rolled-tantalum impactor foil 76 μm thick bonded to a Kapton backing to protect it from the plasma generated by the exploding foil. In the high-velocity experiments, the impactor was a rolled-tantalum foil 30 μm thick. We found that the thinner foils used in the high-velocity experiments were more sensitive to preheating by stray electric currents and rapidly changing magnetic fields. To protect them from preheating, we bonded the high-velocity foils to a Kapton-aluminum-Kapton sandwich. Both impactor designs were in turn bonded to an aluminum exploding foil.

The targets consisted of tantalum foils two to three times the thickness of the impactors. Steps machined in the surface of the targets enabled us to determine the shock velocity by measuring shock transit time across an individual step (see Fig. 2).

The primary diagnostics consisted of two Imacon image-converter cameras operated in the streak mode. In one camera, the slit aperture was aligned over the target steps and a glass flasher block (which produces a flash of light when it is hit and shocked). The glass flasher block shows the shape of the impactor when it reaches the target. At pressures of 0.1 TPa or more, shock temperatures are high enough to produce thermal light emission that can be detected by a fast streak camera at the instant of impact on the glass or when the shock arrives at the free surfaces of the metal target. From this record, we determined the time of shock breakout at two different distances through the target. Figure 3 shows a typical record from this camera. The second camera was used in conjunction with a Fabry-Perot velocity interferometer to obtain a continuous history of the impactor velocity.² Figure 4 shows a typical Fabry-Perot record.

We can measure the impactor velocity (and consequently the material velocity U_p) to $\pm 1.2\%$ with the

Fabry-Perot interferometer. Errors in the shock velocity U_s result primarily from errors in measuring the step height of the target (about $\pm 0.6\%$) and from the intrinsic resolution of the camera (from ± 1 to 5% , depending on the camera model and the streaking rate). In our most accurate experiments, the estimated error in U_p was $\pm 1.2\%$ and in U_s $\pm 2.5\%$, leading to errors of $\pm 2.7\%$ in pressure and $\pm 3.3\%$ in volume at 0.78 TPa.

There is inevitably some distortion of the impacting projectile in any gun system. In a shock Hugoniot experiment, departures from planarity of the impactor must be measured and, if they are significant, a correction must be made. The magnitude of this correction is determined by the deviation from planarity of that portion of the impactor which is in the immediate vicinity of the step in the target.

Typical electric gun impactors arrive at the target with a tilt of about $120\ \mu\text{m}$ (less than 1°), an overall curvature of comparable magnitude, and a surface smoothness of $2\ \mu\text{m}$ or better. In Fig. 5, we show the impact of a tantalum impactor on a glass target; the barrel diameter of the gun is 8 mm and the impact velocity is 7.4 km/s. In measuring the shock transit time, a rarefaction-affected zone near the step must be avoided because the shock pressure and speed will be unrepresentative in this region. This zone will be from one to two times the step height, as shown in Fig. 2. In our EOS experiments, the step heights are only about $30\ \mu\text{m}$. Corrections for nonplanarity must be made only over distances of this order (about $60\ \mu\text{m}$), not over the entire barrel diameter. The correction for nonplanarity in these experiments is on the order of 0.1 ns and is comparable to the resolution of the camera system at the writing speed used with the thin tantalum impactors (5 ns/mm).

The use of thin targets has the advantage of less stringent requirements on impactor planarity. However, this advantage must be balanced against the accuracy with which the step height can be measured and the time resolution of the camera.

Experimental Results

Most of our electric-gun results were obtained with relatively thick impactor foils ($76\ \mu\text{m}$) and targets (152 to $254\ \mu\text{m}$), which reduced impact velocities enough to allow comparison of our data with those reported by others.³ Our shock Hugoniot data agree with

Fig. 4

Typical record obtained with a Fabry-Perot velocity interferometer. The impactor velocity is measured by continuously recording fringes formed by laser light reflected from the impactor surface. When the impactor is moving, the reflected light is Doppler shifted, increasing the separation between the fringes. The impactor velocity is directly related to the separation between the traces. (The multiple fringe patterns are intrinsic to the measuring device; each contains the identical information.) The absence of discontinuities in the traces shows that the impactor is smoothly accelerated without significant shock heating. The material velocity, U_p , is one half the velocity on impact (end of the trace).

Fig. 5

Streak camera record of the impact of a $30\text{-}\mu\text{m}$ -thick tantalum impactor foil on a flat glass target at 7.4 km/s. In this record, the entire barrel diameter is viewed. The actual size of the region of interest to the EOS experiment (shown) is much smaller, roughly twice the typical step height or approximately $60\ \mu\text{m}$. The correction for nonplanarity in these experiments is on the order of 0.1 ns and is comparable to the resolution of the camera system at the writing speed used with the thin tantalum impactors (5 ns/mm).

If conservative extrapolations are made from the system's current operating conditions, Gurney theory predicts that we can achieve pressures of 1.1 to 1.5 TPa in various dense materials.

those obtained with a two-stage gas gun up to its velocity limit (Fig. 6). Pressures reported for the two-stage gun ranged from 57 to 430 GPa.¹

The thinner (30- μ m) tantalum impactors achieved velocities up to 9.7 km/s, extending the Hugoniot curve for tantalum up to 780 GPa (see Fig. 6). Our higher pressure points fall within 3% root-mean-square of a straight line fit to the gas-gun data.

The success of our experiments with tantalum has established the technique for making electric-gun EOS measurements. Our results thus demonstrate the electric gun's capability for EOS measurements in the 1-TPa range for various materials of interest.

Can Higher Pressures Be Reached?

Accelerating metal impactors to the extremely high velocities achieved with all-plastic impactors (up to 30 km/s) would greatly extend the pressure range of current EOS data. To assess the ultimate capability of the electric gun in this application, we need to examine the effect of various system parameters on the velocity of the impactor.

An extension of the Gurney theory to electrically driven flyer plates provides a simple phenomenological model that accurately describes electric-gun impactor velocities over a wide range of foil geometries, impactor masses, and electric-current waveforms. (In its original form, the Gurney theory relates the terminal velocity of an explosively driven metal fragment to the type of explosive and to the ratio of explosive charge to metal weight.) For a fixed barrel length, the velocity of the impactor is given by

$$V_1 = f(I_B)(M/C + 1/3)^{-1/2},$$

where M is the mass-area ratio of the impactor, C is the mass-area ratio of the exploding foil, I_B is the current density in the foil at burst time, and $f(I_B)$ is empirically determined by fitting an analytical function (a power law or polynomial) to the experimental data. When $f(I_B)$ is known, we can use the model to

predict how impactor velocity varies with M , C , and the current waveform. The value of $f(I_B)$ increases with barrel length; by experimentally determining this relationship, we can also use the model to predict the corresponding variation in V_I . We can thus increase impactor velocity either by decreasing M/C or by increasing the barrel length.

We have observed experimentally that the integrity of the impactor deteriorates rapidly beyond a certain flight distance and that the maximum usable barrel length is dictated by considerations of foil stability and interaction with the edges of the barrel. For example, 30- μ m-thick tantalum impactors can be accelerated for 5 mm with excellent quality (as in the EOS data shown in Fig. 6), but at 7.5 mm they become unacceptably distorted.

It would be desirable to understand this behavior and improve upon it. Should foil stability prove a limiting factor, it would help to use impactor foils with a better initial surface finish. Such foils could be accelerated further and thus to a higher velocity. Edge effects may be reduced by using a denser ceramic (such as tungsten carbide) for the barrel of the gun or by more sophisticated hydrodynamic design. The backing and shielding currently used for the impactor are probably thicker than necessary; optimizing them might reduce the mass-area ratio of the composite impactor, resulting in higher velocities.

When the maximum barrel length and the minimum M/C are fixed, I_B remains the variable that can be optimized. We can increase I_B either by decreasing the width of the exploding-foil element, by decreasing system inductance, or by increasing the charging voltage. If conservative extrapolations are made from the system's current operating conditions, Gurney theory predicts that we can achieve pressures of 1.1 to 1.5 TPa in various dense materials.

We believe that the electric gun can produce still higher pressures. Scaling plastic-impactor velocities with Gurney theory predicts velocities up to 18 km/s for composite plastic-aluminum-plastic-tantalum impactors fired under the

On October 15, 1981, John H. Nuckolls received the American Physical Society's Maxwell Prize for outstanding contributions to plasma physics. The citation read "For his contributions to the genesis and progress of inertial confinement fusion. His insight into the fundamental physics issues has served to guide and inspire the technical evolution of the field." An article based on his Maxwell lecture to the Society was published in *Physics Today* (September 1982). Because of the interest that readers of the *Energy and Technology Review* could have in John's views on John's views on inertial confinement fusion, the editors of the *Energy and Technology Review* have agreed to reprint the article in this issue. The work described in

this article has occurred because of the dedication and inspiration of John Nuckolls and his colleagues at LLNL, as well as of hundreds of researchers elsewhere in the United States and other nations. In addition to their work, consistent support for the U.S. Inertial Fusion Program has been provided by the Department of Energy and its predecessors and by the Congress of the United States. This support has led, in 10 years time, to an effort with the accomplishments and scope described in this article. It should be further noted that, although the thrust of this article is directed toward the long-range power-potential of the Inertial Fusion Program, current support and nearer-term goals are defense related.

Feasibility of Inertial-Confinement Fusion

"We can see no insurmountable roadblocks to the practical achievement of electrical power generated by inertial-confinement fusion ... An ICF reactor may have a relatively small containment volume [and] its operation, maintenance, and repair will be relatively simple."

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So concluded the chairman of a Department of Energy *ad hoc* committee of experts in 1979, after a comprehensive review of the U.S. inertial-confinement fusion program.¹ In spite of this positive evaluation, the role of inertial-confinement fusion in the total U.S. energy program continues to be a subject of disagreement.² Before I mention the issues of contention, let me describe inertial-confinement fusion briefly. In a typical reactor scheme, a pea-sized target pellet containing hydrogen isotopes is projected into a reaction chamber, where it is suddenly irradiated with an intense beam of light or ions from a "driver" (Fig. 1). As the surface of the target blasts away, the rocket-like reaction forces implode the target's interior to densities and

temperatures sufficient to cause the hydrogen nuclei to fuse, releasing an amount of energy equivalent to that of a barrel of oil (see *Physics Today*, August 1973, page 46).

Those who are skeptical of the inertial-confinement fusion program have a number of objections. They cite the fact that the magnetic-fusion machines—tokamaks and mirrors—are several years ahead, and they note the time and effort that will be required to solve the technical problems, principally the coupling of the laser beam to the target, the confinement of the fusion explosion, and the development of a practical driver.

During the past three years, however, inertial-confinement fusion has made substantial progress toward solving its principal scientific and technological problems. The program has:

- Achieved efficient beam-target coupling using short-wavelength lasers,
- Achieved high-density implosions with so-called "hohlraum" targets, which we will discuss later,

- Improved the design of damage-proof fluid walls for reactors with high power densities,
- Designed drivers of higher efficiency and lower cost, and
- Planned to utilize the physical separation of the reactor and the high-technology components—the driver and the target factory—which several reactors can share. These developments make possible fusion reactors with minimum cost and radioactive waste.

The Rise of Fusion

In 1942, Hans Bethe, Enrico Fermi, J. Robert Oppenheimer, Edward Teller, and others began to develop the physics of practical fusion. Later, at Los Alamos, fusion research was driven by the determination and technical leadership of Teller. In 1952, seven years after development of the atomic trigger, seismographs worldwide registered the success of the multimegaton inertial-confinement device. In the 1950s, the extraordinary promise of controlled fusion—safe, clean, low-cost energy with inexhaustible fuel accessible to all nations—led to research programs on magnetic-confinement fusion at many scientific laboratories. The 1960s saw the conception and calculation of inertial approaches to controlled fusion, including schemes based on implosions driven by laser and charged-particle beams.

The energy crisis stimulated rapid growth in both the magnetic and inertial-confinement fusion programs in the early 1970s. The inertial-confinement fusion programs at LLNL, the University of Rochester Laboratory for Laser Energies, the Lebedev Institute in the USSR, and Limeil Laboratories in France were joined by the new programs at KMS Fusion Inc., Los Alamos and Sandia National Laboratories, Naval Research Laboratory, Rutherford Laboratory in England, Osaka University in Japan, Max Planck Institute at Garching in West Germany, and laboratories elsewhere. Rapid growth was sustained throughout the 1970s, driven by OPEC policies, fission's political and technical difficulties, and fusion's scientific progress.

In 1980, Congress and the President strongly endorsed accelerated development of magnetic fusion. Although economic difficulties in the United States have postponed this growth, the urgency for fusion continues to increase. The Middle East, source of much of our oil, is unstable. Weaknesses and uncertainties are emerging in the coal-fission strategy for energy independence. Fission energy is increasingly impeded by Murphy's Law (what can go wrong, will) and growing public opposition, while coal energy is generating acid rain and in the 21st century may produce major global climate changes through the CO₂ greenhouse effect.

To contribute to the solution of these energy problems in the next century, inertial fusion must meet several difficult challenges. The DOE experts' committee, which was headed by John Foster, Jr., vice-president of science and technology at TRW Inc., and former DOD Director of Defense Research and Engineering and Director of Lawrence Livermore, noted that "... many problems and unknowns remain, but because of the wealth of promising

Fig. 1

Inertial-confinement-fusion reactor concept known as HYLIFE. A shower of liquid lithium shields the first wall from damaging neutrons, x rays, and hot plasma from exploding fuel pellets. With an average lithium thickness of 50 cm, the neutron damage is sufficiently reduced to increase the lifetime of the first wall tenfold. The neutron-induced radioactivity in the reactor structure is reduced 10- to 100-fold. The average power at the first wall is relatively high, approximately 10 MW/m². More than 90% of this power is absorbed by the liquid lithium.

approaches, it seems plausible that with a continued national effort, a prototype experimental ICF reactor will be in operation by the turn of the century.¹¹ What are these problems, unknowns, and promising approaches?

As we have indicated above, the key idea of inertial-confinement fusion is to ignite small-scale, contained fusion explosions by using high-power beams of energy that implode fuel to superhigh densities and thermonuclear temperatures. For both inertial and magnetic fusion, burn efficiency—the percentage of nuclei that fuse—is proportional to the product of density and confinement time. In magnetic fusion, the fuel density is limited by material properties, so one increases the efficiency of the burn by extending the duration of confinement. In inertial fusion, Newton's laws and thermal velocity limit the confinement time, so one tries to compress the fuel to higher densities. Densities up to 1000 g/cm^3 are energetically accessible via isentropic, or constant-entropy, compression because the Fermi energy—the minimum energy of compressed matter—is much less than the thermal energy at ignition.

There are two basic target designs for inertial-confinement fusion reactors:

- Direct targets absorb the driver beam energy in an outer layer or "shell," which acts directly to produce the implosion.
- Hohlräum targets absorb the driver energy and convert it to x rays, which are contained by a radiation case and are used to drive the implosion.

The hohlraum target designs are classified.

Inertial-confinement fusion must demonstrate that one can achieve a sufficiently high target gain with an affordable driver. Target gain is the ratio of the energy yield of the fusion reaction to the driver energy applied to the target. Assuming driver and implosion efficiencies of 10%, the target gain must be greater than 100. Such a gain is feasible with multimegajoule drivers if three conditions are satisfied: the beam couples efficiently to the target, the fuel is efficiently compressed to 1000 times its liquid density, and a small fraction of the fuel is ignited at the center of the target pellet. The remaining fuel must also ignite by propagation from the central ignited region and burn efficiently.

For practical fusion power, we must develop three technologies to harness the high-gain targets: an efficient and affordable driver that couples efficiently to the target, a practical and economically competitive reactor that incorporates solutions to the problems of cyclic fatigue and stress from pulsed radiation, and a practical target factory. We will address these scientific and technological issues.

By using high-intensity short-wavelength laser light, researchers have improved the absorption of energy by targets and reduced the production of hot electrons, which heat the interior of the fuel pellet and make compression less efficient. Figure 2 shows the results of laser-plasma coupling experiments in which absorption was measured³ as a function of intensity for three laser wavelengths: 1, 1/2, and 1/3 micron. Inertial-confinement fusion targets are designed to operate at intensities of 10^{13} to 10^{15} W/cm^2 . At these intensities, there is 90% absorption of short-wavelength light. Also, fewer hot electrons are produced with shorter laser wavelengths.³ The softer tail of hot x rays in Fig. 3 indicates the reduced production of hot electrons. Experiments at laboratories around the world have confirmed these results.⁴

The efficient coupling of beam and target at short laser wavelengths

Fig. 2

Absorption of laser light by targets increases dramatically with shorter wavelengths. From bottom to top, curves cover data points from experiments at 1, 1/2, and 1/3 micron. (Data from Ecole Polytechnique, University of Rochester, and LLNL.)

confirms our theoretical predictions.⁵ Collisional absorption (inverse bremsstrahlung) competes with collective absorption—principally by way of Brillouin and Raman scattering, self-focusing, or “filamentation,” and the two-plasmon decay instability. At shorter wavelengths, laser light penetrates into denser plasma with higher collision frequency. This raises the threshold for collective instabilities.

Current experiments involve plasmas of millimeter scale length. We must also carry out plasma experiments to test our theoretical predictions at the centimeter scale lengths characteristic of reactor targets. In addition, we need space- and time-resolved measurements of the plasma density profiles and temperatures to confirm our understanding of the details of the laser-plasma interaction.

Scientific Feasibility

The highest density achieved to date in laser implosion experiments with deuterium-tritium fuel is 100 times that of the liquid. As Fig. 4 shows, this superdense material had a temperature of half a keV and a pressure of 10^{10} atmospheres. These results are in good agreement with theory and with detailed calculations using a complex magnetohydrodynamics-fusion computer program called LASNEX. To ignite reactor-scale targets, the deuterium-tritium must be imploded to a thousand times liquid density and multi-keV temperatures. The ignition pressure is about 10^{12} atmospheres. We expect to achieve 200 to 400 times liquid density with the 10-kJ, 1/3-micron Novette laser by 1984-85, and 1000 times liquid density with the 100-kJ, 1/3-micron Nova I laser by 1986-88.

In these high-density Nova experiments, the fusion energy generated by the deuterium-tritium will approach the deuterium-tritium thermal energy.

Figure 4 shows the status and goals of inertial fusion experiments. The experiments that achieved fuel densities 100 times that of the liquid were performed with the LLNL 10-kJ, 1-micron Shiva laser and had a confinement

Fig. 3

Superthermal x rays decrease by over two orders of magnitude when shorter-wavelength laser light is used. Such x rays indicate the presence of superthermal electrons capable of heating the target prematurely. The three x-ray energy spectra shown here are from experiments on gold disk targets exposed to laser light focused to about 3×10^{14} W/cm². From top to bottom, curves cover data points from experiments at 1, 1/2, and 1/3 micron.

parameter (the product of density and confinement time) greater than 10^{14} cm⁻³·s. The Nova I experiments should reach the threshold of ignition—that is, $nt > 3 \times 10^{14}$ cm⁻³·s and temperatures of about 2 keV. Because of the inefficiencies of the driver and the implosion, inertial-confinement fusion has to push nt a factor of 10 further than magnetic fusion to reach conditions that could lead to practical reactors.

The next major challenge for inertial-confinement fusion is to demonstrate scientific feasibility. Before a reactor

Fig. 4

Results of experiments at various inertial-confinement-fusion research facilities. Point at upper left represents the laser-driven implosion of a deuterium-tritium hohlraum target of classified design. Radiochemical techniques showed the density to be 100 times that of a liquid deuterium-tritium mixture. With the Nova laser, researchers plan to implode deuterium-tritium to a temperature of several keV and a density 1000 times that of the liquid.

driver can be designed, funded, and constructed, we must have experimental confirmation of theoretical estimates of the required driver parameters—particularly the driver's energy. The reactor driver is so expensive—perhaps a half billion dollars—that it is not feasible to build it twice as large as required, to provide a substantial margin for error. Consequently, we must generate convincing experimental evidence showing that if the reactor-scale driver were constructed, high target gains would result. This convincing evidence may be used as an operational definition of scientific feasibility.

Physicists will use the Nova laser at LLNL and the light-ion facility at Sandia, the Particle Beam Fusion Accelerator II (PBFA II), to explore scientific feasibility. For directly imploded targets, the central core will reach high densities and the threshold of ignition. Then, even though the volume of material at this high density will not be large enough for the burn to propagate in the pellet, it is feasible to diagnose the important parameters: the density distribution, the temperature, and the amount of contamination of the fuel by the imploding shell. A series of implosion experiments will diagnose the imploding shells. Snapshots will be taken with a laser-driven x-ray backlighting source. In addition, researchers will observe the surfaces of the imploding shells with optical and x-ray streaking cameras to measure the amount of preheating, the velocity history, and the symmetry of the implosion. Finally, they will use the Nova to perform laser-plasma coupling experiments at the scale lengths of the reactor target plasma. The results of these measurements will allow us to predict with sufficiently high confidence how large a target and driver will be required to achieve high gain. The Nova and PBFA II facilities will be completed in the mid-eighties.

A Three-Part System

Let us look at each of the key technologies for inertial-confinement fusion power plants: drivers, targets, and

reactors. There has been substantial progress in all three areas.

With projected improvements in target gains, the driver would have to deliver an energy of about 2 MJ, a peak power of 100 TW, at an efficiency of 10 to 20%. The beams from the driver must focus to spots a few millimeters in diameter across a 5-m chamber to give a power density of 10^{14} to 10^{15} W/cm². The coupling between the beam and the target must be relatively efficient. We will need a repetition rate of ten to twenty implosions per second. The driver should cost less than \$400 million.

The candidates for the driver are KrF, CO₂, and free-electron lasers, and beams of heavy and light ions. We are optimistic that light ions will be able to focus to 10^{14} W/cm². Researchers have already focused light-ion beams to 10^{12} W/cm². We have not yet achieved efficient beam-target coupling with CO₂ lasers. The 40-kJ Antares laser—the world's largest CO₂ laser, now under construction at Los Alamos—will help explore this problem. Imaginative targets are now being tested on the 10-kJ CO₂ Helios laser at Los Alamos.

With current technologies, most of the proposed drivers would cost approximately \$400/J, or \$800 million for 2 MJ. Many of the candidates are making steady progress in reducing their costs. We foresee a factor-of-two cost reduction to about \$200/J. Light-ion accelerators and advanced lasers may be significantly cheaper. When the cost of the fraction of the reactor needed to power the driver is included, highly efficient drivers such as heavy-ion accelerators with 25% efficiency may have nearly a twofold cost advantage over marginally efficient drivers such as lasers with 5% efficiency. The table summarizes the status, strengths, and weaknesses of the driver candidates.

Targets. Both hohlraum and direct targets are under development. These target designs include margins of safety to cover uncertainties in the implosion and burn.

Targets for inertial-confinement fusion are fabricated from very small masses of low-cost materials (except for

tritium, which is regenerated in the reactor). Target costs, then, are dominated by the capital and operating costs of the target factory. There are plausible solutions for the principal fabrication problems: surface finish, on-line inspection, and high production rate.

In hohlraum targets, as we mentioned, the energy of the driver beam is absorbed and converted to x rays, which are contained by a radiation case and used to drive the implosion. This gives the hohlraum target one of its important advantages—improved implosion symmetry. One can achieve symmetry without requiring the beams of the driver to be uniform and symmetrically arranged. In some reactor designs, just two beams drive the target. It is more difficult to implode directly driven targets symmetrically with a few beams. Another important advantage of hohlraum targets is that they couple efficiently to several of the driver candidates—possibly including CO₂ lasers. Researchers at LLNL have done many experiments with hohlraum targets using the 1-micron Shiva laser and the 1-, 1/2-, and 1/3-micron Argus laser. The experimental results are in excellent agreement with detailed LASNEX calculations and with theoretical scaling relationships.

Directly imploded targets appear to be advantageous at driver energies under 100-kJ driver energy. Researchers at KMS, NRL, the University of Rochester, and laboratories outside the U.S. are attempting to develop directly imploded reactor targets with both the required implosion symmetry and as high an implosion efficiency as that of the hohlraum targets. Implosion efficiency is the overall energy efficiency with which the beam couples to the target and compresses the fuel. An important problem is how to generate and combine many ultrasmooth laser beams or ion beams.

Significant improvements in targets for inertial-confinement fusion are possible. Compression of the fuel to higher density is theoretically possible. Because the scaling parameter for the burn efficiency of the fuel is the product of the mass of the fuel and the

Driver candidates.					
Requirements	CO ₂ laser	KrF laser	Free-electron laser	Heavy-ion accelerator	Light-ion accelerator
Efficiency (10-20%)	?	?	+	++	+
Focusing (10 ¹⁶ -10 ¹⁵ W/cm ² at 5 m)	+	+	+	+	?
Target coupling (10%)	?	++	++	++	+
Repetition rate (10 ³ -10 ⁴ Hz)	+	+	++	++	+
Cost (\$200/J at 2 MJ)	+	+	+	+	++
+: could meet requirements.					

square of its compression, even a 40% increase in density would decrease the fuel mass and driver size by a factor of two.

It may also be feasible to make significant improvements in the target's implosion efficiency. Nonablative implosion schemes may have a higher implosion efficiency. This could decrease the size of the driver and increase the target gain by a factor of two.

Finally, current target designs provide a substantial margin for error. We may be able to relax these conservative design criteria when we have a greater experimental and theoretical understanding of the implosion and burning of the targets. Such a relaxation could provide another factor-of-two decrease in driver size and increase in target gain.

We hope to achieve a twofold reduction in driver energy requirements and a twofold increase in target gain.

Figure 5 relates the performance of the target to driver and reactor requirements.⁶ The lower band in this figure shows the calculated gains of our conservative targets. The optimistic band represents an improvement in target performance by almost a factor of four. The design point is at 2 MJ with a yield of 600 MJ—a gain of 300. For a 1-GW_e reactor and 10 to 20% efficient driver, the overall energetics would be robust. Driving fusion with a KrF laser of 7% efficiency would give a good overall energy gain for optimistic target performance but only a marginal gain

Fig. 5

Relationships of performance parameters of target, driver, and reactor for a 1-GW_e power plant burning deuterium-tritium fuel. Inertial-confinement-fusion reactors may be economically competitive with light-water fission reactors if they can be designed to have a 2-MJ driver energy (at a direct cost of \$200/J), 600-MJ target yield, driver efficiency η_d greater than 15%, 5-Hz reactor repetition rate, and 10- to 20-Hz driver repetition rate. The driver would be shared by two to four reactors.

with projected target performance. The lines of minimum necessary driver efficiency in Fig. 5 are based on the assumption that the product of the efficiency of the driver and the gain of the target is 20. Then the driver uses 10 to 15% of the power the reactor produces.

Reactors. A critical issue for inertial-confinement fusion reactors is the pulsed thermonuclear explosion, which could cause unshielded reactor walls to fail by cyclic fatigue or ablation. In the LLNL HYLIFE fluid-wall design (Fig. 1), there is a shower-like set of fluid jets of liquid lithium between the exploding target and the first wall.⁶ The fluid layer, 0.5 to 1 m thick, protects the first wall from the pulse of radiation and hot plasma. It also reduces by a factor of about 10 to 100 the activation and neutron damage in the first wall.

Another issue² is the feasibility of containing small thermonuclear explosions, each releasing an energy equal to a few tenths of a ton of TNT. The impulse of an explosion is proportional to the square root of the product of mass and energy. Although the energy, which is mainly radiated into the fluid curtain by neutrons and x rays, corresponds to a significant fraction of a ton of TNT, the mass of the target is a million times smaller because the energy is generated by 10-MeV thermonuclear reactions rather than by 1-eV chemical

reactions. Thus, the impulse is reduced a thousandfold because the mass is a million times smaller. In addition, the lithium is sufficiently massive and far from the wall that its interaction with the wall is largely nonimpulsive.

Radioactive target debris is also an issue. Any material in the target besides deuterium and tritium will be activated by the intense flux of neutrons. Debris is also activated further when it is recirculated in the liquid lithium inside the reactor. In targets designed to minimize radioactive debris, the most significant radioactive material is lead. The dominant radioactive isotope of lead is lead-203, with a half-life of 53 hours. Other radioactive isotopes are negligible. A few months after the lead has been separated from the lithium, the radioactivity has decayed by a large factor, and the lead may be recycled in the target factory. The total mass of radioactive target debris generated during the 30-year lifetime of the reactor is a few tons.

In the HYLIFE scheme (Fig. 1), beams come to the target from drivers that are of about 100 m from the reaction chamber, which has a characteristic dimension about 5 m. The average product of density and thickness through the pattern of lithium jets is about 40 g/cm². Figure 6 shows the lifetime of a first wall made of low-chromium, nickel-free steel as a function of the thickness of the lithium.⁶ In fusion reactors, at least two neutronic effects reduce the lifetime of the first wall: atomic displacements and the generation of helium. For a lithium thickness of 0.5 m, the first wall's lifetime is about 30 years, so it would not have to be changed during the lifetime of the reactor. Without the fluid shield, the wall would last about five years and would have to be replaced by remote control several times during the life of the reactor.

Because the time required for a splattered droplet to fall 5 m is about 1 s, the current HYLIFE design is limited to a repetition rate of about 1 Hz. To increase the repetition rate to 5 Hz so that we can fully exploit both high-repetition-rate drivers and the heat

capacity of the flowing lithium, which is several times larger than required, we must improve the design. With evolutionary improvements, 3 Hz may be feasible. Several radical variations would take us beyond that. In the HIBALL scheme,⁷ for example, porous silicon carbide tubes would confine the streams of liquid lithium-lead alloys. These tubes would also reduce the liquid flow rate.

With respect to feasibility, the conclusions of the Foster Committee are valid: the number of promising approaches is in reasonable balance with the problems and unknowns, and no insurmountable roadblocks are evident. Beyond scientific feasibility, a major challenge for the inertial-confinement fusion program is to realize the potential advances: higher gain targets with reduced driver requirements; cheaper, high-efficiency drivers; and fluid-wall reactors able to withstand high repetition rates.

Utility

We now turn our attention to the two crucial questions of economic and environmental utility for all approaches to fusion:

- In the limit of its best performance, is fusion economically feasible?
- Do fusion's economic and environmental potentials justify accelerated development, particularly in light of the possible limitations of coal and fission energy? Unfortunately, fusion's economic and environmental potentials are not very well known. Nevertheless, I will attempt to answer these questions assuming we can achieve scientific feasibility and the potential advances that we have discussed.

Were it not for the potential existence of the "fusion hybrid" reactor—and the liquid-metal fast breeder reactor—the long-term escalation of fossil and fission fuel costs and the cost of externalities such as radioactive waste and safety hazards might make fusion economically competitive even at twice the cost of current fossil and fission energy systems. Fusion hybrids produce fuel for fission reactors. Most first-generation inertial and magnetic

fusion systems are estimated to be roughly a factor of two more expensive than light-water fission reactors. However, fusion hybrids would cap any increase in the cost of fission energy due to escalating fission-fuel costs at only 20% of the total cost of the light-water reactors themselves, because a hybrid costing as much as three light-water reactors could supply fuel for 15 light-water reactors. Furthermore, the National Academy of Sciences Committee on Nuclear and Alternative Energy Systems estimates that externalities are not significant. Liquid-metal fast breeder reactors would also limit the escalation of fission fuel costs.⁸

Nonetheless, because U.S. energy costs are less than 10% of the GNP, our society could decide to buy an environmentally superior energy system costing twice as much as a minimum-cost energy system. However, U.S. industry powered by a doubly expensive energy system, employing expensive labor, would be less competitive with foreign industry powered by minimum-cost energy systems. This would be particularly true if foreign industry invested its energy system cost savings in automation, advanced technology, and research and development.

An important factor that may make possible inertial-confinement fusion power plants that are economically competitive with fission is driver

Fig. 6

First-wall lifetime, as a function of the thickness of the protective liquid lithium curtain. These estimates are for a 2.25 Cr-1.0 Mo-steel wall in a 10-MW/m² fusion reactor. A half meter of shielding extends the lifetime from a few years to 30 years. Uncertainties are indicated in the effects of neutron-induced helium production and atomic displacements. The upper and lower curves for helium production shown here represent 1000 and 500 atomic parts per million of helium, respectively. The upper and lower displacement damage curves represent 330 and 165 displacements per atom, respectively. (From Ref. 6.)

separability, which the Foster Committee discussed: "One of the chief advantages of ICF is that ... the driver is separate from the reactor vessel itself, and can be removed some distance. This means that an ICF reactor may have a relatively small containment volume; that its operation, maintenance, and repair will be relatively simple; and that the most expensive components will not be subject to neutron bombardment and activation. The potential also exists for a great variety of power plant sizes and configurations." Furthermore, a separated driver can drive several reactors, and time-shared target factories are feasible as well.

For inertial and magnetic confinement approaches where time sharing and fluid walls are not feasible, one can reduce costs and radioactivity by other means, such as developing cheaper superconducting materials that sustain higher magnetic fields (to increase the power density), and developing first-wall materials with longer lifetimes and less neutron-induced radioactivity.

The high cost of first-generation fusion reactors relative to light-water fission reactors is principally due to three factors:

- The costs of fusion technology equipment—inertial confinement's driver and target factory, or magnetic confinement's superconducting magnet, beam heater, and high-vacuum system.
- Fusion's lower power density.
- Fusion's more complex first-wall and heat-transfer structures.

Reducing Costs

Even if fusion-technology equipment were free, some approaches to fusion power would be more expensive than light-water reactor power because of the second two factors. To be economically competitive, the cost premium due to these three factors must be less than about 50%—20% for fission fuel escalation and 25% for unescalated fission fuel-cycle costs. In light-water reactors, fuel-cycle costs are approximately 25% of the total and are not included in capital costs. To a first approximation, fusion reactors could compete economically with light-water reactors even if

they were almost 50% more expensive to build. Here is one possible accounting of the extra costs:

- The cost of the driver is less than 20% of the cost of a light-water reactor. This would compensate for the 20% increase in the cost of fission energy due to the escalation of fuel costs.
- The cost of the targets and target factory is less than 25% of the cost of a light-water reactor. This compensates for the light-water reactor's 25% fuel-cycle expense. The capital cost of the reactor and the rest of the power plant must not be more than that of a light-water reactor.

The cost of the driver may be reduced to 10 to 20% of the cost of a 1-GW_e light-water reactor—approximately \$150 million not including interest charges. For multimegajoule short-wavelength lasers and heavy-ion accelerators, one can achieve such a reduction by reducing the driver costs twofold to \$200/J at 2 MJ, improving the targets twofold (to reduce the required driver energy to 2 MJ) and by using a single driver for two or more reactors. We have already discussed these driver and target improvements.

Multireactor systems with time-shared drivers are apparently feasible. Laser and heavy-ion beams can be switched rapidly and propagated over 100-in distances; these drivers are capable of 10- to 20-Hz repetition rates with relatively small increases in cost. Some high-energy accelerators, from which heavy-ion technology is derived, show high capacity factors. If a few additional beams are designed into multibeam fusion lasers, then individual beams could be shut down for repair without affecting the operation of the reactor. A four-reactor site with 4-GW_e total electrical output would generate roughly 1% of the projected U.S. electrical energy in 2010 and less than 0.5% in 2050, assuming a slow 2% energy growth rate.

Driver technologies such as light-ion accelerators and advanced lasers may be cheap enough so that with an additional factor-of-two improvement in target performance, fusion reactors as small as 0.5 GW_e would be

economically competitive with light-water reactors. These small reactors would be highly advantageous for initial commercialization.

The estimated capital and operating cost of the target factory is 10 to 30% of the cost of a light-water reactor.⁷ Several factors limit the cost. These include the factory's small size, complete automation, and long-term high production rates, as well as its location at the power plant and the automated transport of pellets to the reactor chamber.

The capital cost of a HIBALL fluid reactor and the rest of the power plant without the driver and target factory is estimated to be approximately equal to the capital cost of a light-water reactor.⁷

Inertial-confinement fusion reactors may have an exceptionally high capacity for optimization. The target is small and cheap and may be improved during the lifetime of the reactor. The driver and target factory, being separate from the reactor, are not strongly activated by the fusion neutrons. Utility-bankrupting meltdown accidents are not possible when the reactor is switched off. Based on our experience with fission reactors, this potential for incorporating technological advances and responding gracefully to Murphy's Law is important for the development of practical high-technology power plants.

Deuterium-burning reactors would have significant environmental advantages over deuterium-tritium reactors and might also be cheaper. The radioactivity of the first wall would be reduced because fusing deuterium produces fewer and less energetic neutrons. To eliminate the tritium generated in the liquid-lithium curtain, one would protect the first wall with a material such as liquid lead. By eliminating the lithium and minimizing the tritium hazard and first-wall radioactivity, fusion would approach its full environmental potential. Because the fuel burn occurs inside the target and because fewer neutrons are produced, deuterium-burning inertial-confinement fusion reactors would have a higher power density than deuterium-tritium-burning reactors. Such a deuterium-

burning inertial-confinement fusion system may be significantly cheaper than a light-water reactor, depending on the size of the driver required to achieve high gains with deuterium-burning targets.

Attractive fusion-fission hybrids and hydrogen synfuel producers are also feasible—hybrids, because neutron and tritium breeding is possible within the first wall, and synfuel producers, because reactors with walls at very high temperatures may be feasible.⁹

Options for the Future

There are major uncertainties in our understanding of the CO₂ greenhouse problem. However, if calculations are correct, before the middle of the 21st century it may be highly desirable to rely on nonfossil fuels to generate more than 50% of the total energy. U.S. fission energy could not be accelerated rapidly enough to sustain historic economic growth rates, and is now in the process of losing its competitive advantage.

One option would be to accept slower economic growth and the associated loss in GNP.

A second option would be to import uranium and zero-defect, low-cost "Toyota" and "VW" fission reactors. These two options would be extraordinarily expensive, costing many trillions of dollars over several decades.

A third option would be to counteract the warming caused by the greenhouse effect with global climate control—seeding the stratosphere with aerosols to increase Earth's albedo, for example.¹⁰ The greenhouse warming due to the projected doubling of the CO₂ in the atmosphere might be counteracted by increasing the albedo by 2%. Global climate control would require an unprecedented degree of international cooperation. The best strategy might be to intensify energy conservation, revitalize the U.S. fission industry, and accelerate the development of economically competitive fusion and solar energy.

Figure 7 shows the results of a recent calculation of the CO₂ greenhouse effect by NASA scientists.¹¹ Their

Fig. 7

Projected average global temperature change due to CO_2 produced in the combustion of fossil fuels. The temperature is expected to rise above the background noise in the time period 1990 to 2000. The graph shows the results of various economic growth rates and strategies of fuel use. The upper and lower slow-growth curves represent results of calculations assuming no coal phaseout and a coal phaseout beginning in the year 2020, respectively. "Business as usual" scenarios generate average temperatures approaching those of the dinosaur age. In the slow-energy-growth scenario, the temperature increase may be limited to 1.5°C by starting to phase out coal burning fairly early in the 21st century. (From Ref. 11.)

model predicts the average increase in global temperature due to CO_2 from the burning of fossil fuel. The calculations indicate that the temperature increase will become observable in the period 1990 to 2000. With slow (2%) energy growth rates and no reduction in the use of coal, the temperature increases 2.5°C by 2100. If coal burning is phased out in the period 2020 to 2060, the temperature increase is only 1.5°C . This is not much more than the 1°C temperature increase that is predicted to occur because of the CO_2 already added to the atmosphere. When we take into account the warming due to both CO_2 and trace gases, the time to begin phasing out the burning of coal may advance 20 years to the early 21st century.

Optimists argue that the net greenhouse effect may be beneficial. Part of the USSR might become viable farmland, although part of the U.S. prime middle western farmbelt may become drought-prone. The growing season would lengthen and plants might grow faster. Melting of the West Antarctic ice cap and flooding of the world's coastal cities probably would not occur in the 21st century. However, while the rate of change of climate may be difficult even for affluent civilizations, it could be disastrous for underdeveloped nations with populations that already border on starvation.

Coal burning will also cause serious environmental problems such as acid rain.

Because it takes 40 years to install a new energy technology, the candidates to replace fossil fuels should be demonstrated in this century. The most highly developed candidate is fission. An important question is, could fission meet U.S. energy needs by 2030? The U.S. fission industry is being crippled by Murphy's Law. No new domestic orders for reactors are projected for 5 to 10 years. The probability of a reactor-disabling (and utility-bankrupting?) accident is estimated to be as high as one in thirty per reactor lifetime. Alvin Weinberg has called for the development of a second-generation light-water reactor, 10 to 100 times more reliable than current designs.¹²

A recent study¹³ by TRW and LLNL scientists—including Teller, a leading proponent of the coal-fission energy strategy—concluded that with moderate energy growth rates fission could generate only about 15% of the total U.S. energy by 2040. Inspection of these calculations shows that with either slow (2%) energy growth rates and limited energy conservation or with historic energy growth rates and continuing improvements in conservation, fission could generate only about 30% of the U.S. energy by 2040 to 2050. With both slow growth and strong conservation, fission energy would be adequate. Fission energy has a limited rate of acceleration because of the 10- to 20-year doubling time of liquid-metal fast breeder reactors, the finite U.S. supply of fuel for light-water reactors, and realistic deployment rates for a newly developed fast-breeder-reactor technology. Because one fusion-fission hybrid could support 15 light-water reactors, an accelerated hybrid program in conjunction with a revitalized, competitive U.S. fission industry could generate 50% of the total U.S. energy by 2030, even assuming historic growth rates.

The projected international energy problem is much more severe than the U.S. problem. In the next 50 years, rapid international energy growth will

be driven by a doubling of the population and steady per capita energy growth. Energy demand is projected¹⁴ to increase three- to fourfold. This would require a tenfold increase in coal production and/or 10 000 nuclear reactors. The market for practical fusion reactors would be on the order of \$10 trillion. In comparison to the multitrillion-dollar costs associated with these various options, the estimated \$20 billion cost of fusion development is relatively small.

In the 1980s, the magnetic and inertial-confinement fusion programs will develop an improved understanding of fusion's economic and environmental potentials. There should be a coordinated management of these programs with a common basis for program planning and evaluation. Based on our present incomplete understanding, I believe the answers to the two crucial questions of utility are positive: economically competitive fusion systems are potentially feasible, and the accelerated development of fusion is justified by fusion's economic and environmental potentials, especially in light of the significant limitations of coal and fission energy.

Because of the limitations of the coal-fission strategy, we may need fusion and other alternative energy sources by the early 21st century. The U.S. fusion program should be accelerated to develop practical power plants on this timescale.

The development of fusion energy merits high national priority and a

major commitment of our scientific and technological resources. □

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