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About the Cover

Cigarette smoke is only one of the many agents capable of or suspected of inducing changes in human chromosomes. Until now, however, few methods could be applied directly to measure mutations or other forms of genetic damage in humans exposed to potentially noxious substances. We have validated and standardized a bioassay for measuring such changes in human beings and have used it to study exposure in cigarette smokers. The results demonstrate the feasibility of using the method as a tool of industrial hygiene. For more information, see the article beginning on p. 1 of this issue.

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About the Journal

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Gallium Arsenide Amplifier

Integrated circuits made from silicon have completely transformed the electronics industry. As the technology has matured, we have become accustomed to seeing a seemingly never-ending parade of ever-more-sophisticated devices and ever-lower prices.

In some respects, this continual improvement is still going on, but in others the parade is slowing down. Designers of ultrafast linear amplifiers

are reaching practical limits in the properties of silicon itself and the methods available for fabricating it into integrated circuits. The demand for faster amplifiers continues, however, especially in our diagnostic instrumentation. To satisfy this demand, it appears that it will be necessary to take a different approach to developing the next generation.

One promising possibility, which we have been pursuing since 1977 (see *Energy and Technology Review* for August 1981, p. 1), is to substitute a new material—gallium arsenide (GaAs)—with more favorable physical properties. Transistors made of GaAs respond to an input signal faster than those made of silicon (using comparable fabrication technology) because electrons travel faster under a given driving electric field in GaAs than in silicon.

Last year, our efforts in this line reached a first milestone with the demonstration of the small-scale integrated amplifier circuit shown in Fig. 1. The circuit showed voltage gains of $5\times$ (with 50- Ω source and load impedances) and a frequency response of dc to 0.9 GHz. The speed of this embryonic device is comparable to the best that can be achieved with commercial, highly developed, silicon-based integrated-circuit amplifiers, as indicated by the input and output signals shown in Fig. 2. This device is just a first step toward our goal of developing even faster amplifiers.

Our purpose in developing this linear amplifier is not really to develop

Fig. 1

Our GaAs integrated-circuit amplifier, greatly magnified (see scale). Even though this device is still in an embryonic stage of development, its frequency response is roughly comparable to that of the fastest commercially available silicon-based amplifiers.

Input

Output

Fig. 2

Pulse response of the gallium arsenide amplifier. (a) Input pulse, with a rise time of about 50 ps. (b) Output pulse, with a (negative) risetime of about 400 ps.

a new amplifier technology but rather to provide state-of-the-art amplifiers for our diagnostic applications. Frequently, our special requirements call for amplifier characteristics that are difficult to obtain on the market. With an in-house GaAs capability, we can furnish amplifiers and other circuits tailored to our needs.

Meanwhile, researchers in other institutions, stimulated perhaps by the progress in GaAs integrated circuits, have produced vastly improved (but still experimental) silicon integrated circuits. As a result, the relative merits of silicon and gallium arsenide are the subject of active debate, and the competition is intensifying.

We are now working on the more complex GaAs amplifier circuit shown in Fig. 3. This amplifier is designed for dc to 1.5 GHz bandwidth and $10\times$ gain. In the following phase, we plan to extend the amplifier bandwidth to 3 GHz and to introduce some small- and medium-scale digital circuits operating with gate delays that are less than 100 ps.

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Key Words: integrated circuits—gallium arsenide, silicon.

Fig. 3

The more advanced gallium arsenide amplifier we are now developing. We anticipate a gain of $10\times$ and a bandwidth from dc to 1.5 GHz.

20 CIGARETTES

Measuring Chromosome Changes in Exposed People:

Cigarette Smokers

CHROMOSOME CHANGES DETERMINED

We have validated a bioassay for quantifying cellular change in human beings exposed to potentially hazardous agents. We have applied the bioassay to a group of Laboratory workers to determine the effects of smoking on chromosomes.

Man is continually exposed to a variety of natural or synthetic agents. These include physical agents such as ultraviolet light, cosmic rays, and heat, and chemicals present in the diet or environment. That such substances are able to modify the genetic material—deoxyribonucleic acid (DNA)—is well known, and it is therefore reasonable to expect that they have played a significant role in the induction of mutation (permanent, heritable change in DNA) and in the process of evolution.

The proliferation of technologies associated with the growth of industry has produced a diverse spectrum of new substances to which man is exposed. There is a clear need both to identify any potential genetic hazard associated with these substances and to estimate their biological impact on people.

Many short-term biological assays now available can identify potential mutagens (substances that produce mutation) and carcinogens (substances that produce cancer). Most of these procedures are performed on cells in tissue culture or in animals. Few methods can be applied directly to the human to measure mutations or other forms of genetic damage induced by exposure to potential mutagens or carcinogens. We are aggressively trying to remedy this deficiency. The Laboratory is developing new procedures to measure mutations that lead to the production of abnormal hemoglobin, the loss of cell surface

proteins, and the loss or modification of enzymes used in the synthesis of DNA.

It is possible to detect and measure gross changes in DNA by looking at chromosomes through the light microscope. These chromosomal alterations include overt breakage and rearrangement of the chromosomes within the cell (chromosomal aberrations) and also more subtle changes involving the exchange of parts of a single chromosome, a process called sister chromatid exchange (SCE). The significance of mutations and chromosome alterations for human health is not known with certainty, but these endpoints may be useful indicators of cancer risk. This hypothesis is yet to be properly validated in long-term animal or human cancer studies. At the least, however, such alterations are indicators of exposure to noxious substances and thus can serve as biological dosimeters in an industrial hygiene program. To validate and standardize a bioassay appropriate to such programs, we have studied SCE in a group of cigarette smokers selected from the Laboratory's work force.

Sister Chromatid Exchange

When physical or chemical substances enter a cell, they can modify its DNA in many ways. Some can directly break the DNA. Others can form covalent chemical linkages to the DNA, subsequently modifying its structure. SCEs are most efficiently induced by chemicals of the latter

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type.¹ Figure 1 is a photomicrograph showing actual SCE in the chromosomes in a human lymphocyte (a type of white blood cell); the chromosomes have been stained to make SCEs visible. One half of each chromosome (called a chromatid) stains light, and the other half stains dark. (Differential staining is achieved by growing the cells in a special way.¹) In some chromosomes, the dark chromatid exchanges with the light chromatid, hence the term "sister chromatid exchange."

Fig. 1

Photomicrograph of chromosomes in a normal human lymphocyte. The chromosomes are stained to differentiate them longitudinally into two chromatids, one dark and one light. Arrows indicate sites along the chromosome where the DNA has been broken and switched from one chromatid to the other (sister chromatid exchange). These events can be counted directly through the light microscope. About 7 to 10 of these SCEs are found in a normal cell.

The baseline level of SCEs found in human cells not exposed to exogenous mutagens is about 7 to 10 per cell. At the molecular level, the site of each exchange represents a breakage and rejoining of four strands of DNA. If breakage and rejoining occur without permanent damage to the DNA, the biological consequences of an SCE are

negligible. However, if the SCE process occurs imprecisely so that the DNA is not restored to its original configuration, a mutation can result. This could be the case if the rejoining of the four DNA strands did not result in the same DNA nucleotide sequence (i.e., order of DNA bases that specifies the code for proteins) that existed prior to the exchange. This may occur, for example, if the breakage of the four strands did not occur at precisely the same nucleotide position in all four strands.

In a series of experiments conducted over the past several years, we measured the induction of mutations and SCEs in cells treated in culture with one of eight mutagenic agents—seven chemicals and ultraviolet light. We used cells from a Chinese hamster, since these cells are easily grown in culture medium, and both mutations and SCEs can be easily quantified in the same treated cell population. Figure 2 summarizes our results. We have plotted the frequency of SCEs induced per cell against the frequency of mutations induced at a single gene locus, *hprt*, that codes for an enzyme involved in the synthesis of DNA. Although the data points themselves are not plotted, the relations are linear by statistical fit, suggesting that for any one agent the presence of SCE in a cell also indicates the occurrence of mutations. The fact that the slope of the line is different for each agent implies that the efficiencies of SCE induction and mutation induction are different for each agent.

We and other laboratories have examined several other substances that produce essentially the same linear relationship between SCE and mutation. We conclude that, although the presence of an induced SCE in itself may not be a mutagenic event, cells with a high SCE frequency are likely to have a high mutation frequency. As we have noted, because the health consequences of an increased SCE or mutation frequency in human somatic cells are uncertain, such findings must be interpreted with caution until properly validated.

Developing a Bioassay

A cell type useful for the analysis of sister chromatid exchange in humans must be, first, readily accessible; second, capable of undergoing proliferation *in vitro* so that its chromosomes can be made visible; and, third, representative of cells exposed to agents following their injection, ingestion, inhalation, or absorption through the skin. Although no single cell type optimally satisfies all these criteria, some unique advantages are offered by the circulating lymphocyte. As the carrier of nutrients, metabolites, and other chemicals to and from the cells of the body, the peripheral blood circulates to every organ. Exposure of blood cells to a toxic agent localized in a subset of cells in the body therefore depends on, and is potentially limited by, the transport of the agent (or its metabolites) from the cells to the blood. For most exposure routes, then, the circulating lymphocyte in the blood is a plausible recipient cell.

Although the lesions that eventually produce SCEs are induced in lymphocytes in the body, their effects on the chromosomes are not manifested until the lymphocytes are placed in a culture medium. (SCEs form only in dividing cells. Because lymphocytes are non-dividing cells within the body, they do not form SCEs *in vivo*.) This implies that the lesions persist in the circulating lymphocytes until they are cultured.

In our cellular assay, we first draw a sample of blood (1 to 2 ml) from an individual and place the blood lymphocytes in tissue culture for about 72 h. The chromosomes in the cells are then held in mitosis (a period during cell growth in which the chromosomes condense to a size that can be viewed with the microscope), fixed on microscope slides, and stained. Through a microscope, we count the number of SCEs in each chromosome. Usually, we analyze chromosomes from 40 to 80 cells per person, a process that requires about six hours.

To test the sensitivity of SCE as a measure of human exposure to suspected mutagens, we obtained

blood samples from cancer patients undergoing chemotherapy, which repeatedly exposes such subjects to moderately high doses of known mutagens or toxic agents in the form of drugs to treat the cancer. Table 1 compares the lymphocyte SCE frequencies observed in six chemotherapy patients with those found in a control group not exposed to any known mutagen. The mean SCE frequency in the control group was about 9.3 per cell, with a standard error of ± 0.4 SCEs per cell; in contrast, the values for the treated patients ranged from 9.5 to 42.5 per cell. We note that,

Fig. 2

In a series of experiments with Chinese hamster cells in culture, we measured the induction of both SCEs and gene mutations in the same treated cell population. The linear relation for each agent suggests that sister chromatid exchange can be used as an indicator of mutations. The agents used were mitomycin C (MMC), decarbamoyl mitomycin C (DCMMC), porfiromycin (PORF), proflavin sulfate (PRO), ultraviolet light (UV), ethyl methanesulfonate (EMS), ethyl nitrosourea (ENU), and a synthetic mutagen, ICR 191.

Table 1 Frequency of sister chromatid exchange in lymphocytes of patients receiving chemotherapy for cancer.

Subject	Chemotherapy	Mean SCEs/cell
Controls ^a	none	9.3
A	adriamycin, cytoxan, cis-platinum	14.5
B	adriamycin, cytoxan, methotrexate, 5-fluorouracil	27.7
C	alkeran, 5-fluorouracil	18.3
D	velban, 5-fluorouracil	24.7
E	5-fluorouracil	42.5
F	5-fluorouracil	9.5

^aTwenty subjects.

although individuals E and F received the same chemotherapy, their SCE response was dramatically different. This result suggests that exposure to a physical dose of a substance does not translate straightforwardly to an equivalent biological dose to the lymphocytes, individual responses being markedly affected by biological processes.

Because the agents to which these patients were exposed are highly toxic and mutagenic, the observed SCE frequencies (on average, a two-fold increase) represent an upper limit on those we may expect in any human population study. Because such potent mutagens, or high doses, are unlikely in occupational or environmental exposure, we found it essential to standardize the bioassay to enable us to detect relatively small increases in SCE frequency.

Our goal was to control carefully all factors involved in sample collection, cell culture, and data acquisition. In a major study to measure variability in SCE frequency among unexposed individuals, we found that our procedures enable us to detect, with 98% assurance, a 10% increase in mean SCE frequency among 10-subject groups. Among 5-subject groups, these same procedures lose sensitivity so that we can only detect a 20% increase in SCE frequency. The high sensitivity of

our procedures means that, because we need not test large numbers of individuals, the measurement of SCE in human populations is a powerful bioassay.

Another large study gave us further confidence in our technique. In this study, we evaluated SCE frequencies in nonsmoking, "unexposed" individuals. We found no significant difference either between males and females or among individuals between the ages of 21 and 65. These initial results suggested the feasibility of applying our technique to studies of human populations.

Sister Chromatid Exchange in Cigarette Smokers

If the incidence of SCEs in lymphocytes is a reliable indicator of biological dose, it should ideally increase with dose. (In some cases of chronic exposure, the complex kinetics of DNA lesion repair and lymphocyte turnover may complicate a dose dependence interpretation). We chose to evaluate the SCE assay as measure of exposure in a sample of cigarette smokers, whose increased susceptibility to lung and other cancer, together with the presence of mutagens in cigarette smoke, is well documented.

In a carefully designed initial study, we obtained a random sample of individuals from LLNL's work force. With their cooperation, we sought to determine whether SCE frequency in their lymphocytes would correlate with the number of cigarettes each smoked per day. Each subject completed a questionnaire concerning health, occupation, and potential exposure at home or at work. Individuals with known confounding factors, such as disease or certain medications, were excluded from the study. The final test population consisted of 95 individuals of both sexes. Of these, 53 never smoked, 12 smoked up to one pack per day, 26 smoked up to two packs per day, and four persons smoked up to three packs per day.

Figure 3 shows the results of our analysis. The mean SCE frequency of

each group increased with the number of cigarettes smoked per day. The increase among smokers is statistically significant when compared with the group mean (9.3 SCEs per cell) of the nonsmokers: 12% increase (10.4 SCEs per cell) for one pack a day, 20% increase (11.2 SCEs per cell) for two packs a day, and 35% increase (12.5 SCEs per cell) for three packs a day. If we plot the SCE frequency against the number of cigarettes smoked by each individual per day, the resulting regression line has a slope significantly different from zero, yielding the relation

$$\text{SCEs per cell} = 9.2 + 0.054x,$$

where x is the number of cigarettes smoked per day. This slope is about 20-fold less than that obtained for the increase in SCE frequency after human lymphocytes were directly exposed in cell culture to low-tar condensate from cigarette smoke (measured in experiments at other laboratories). The increases we observed in smokers are thus reasonable, considering that the exposure is chronic and that the mutagenic substances in cigarette smoke are dilute compared to the condensate used in cell culture and must be transferred from the lung to the lymphocyte in the circulating blood. The data also reflect the variation in SCE frequency observed among individuals. SCE frequency among nonsmokers ranges from about 5 to 13 per cell. The reason is unknown but could well be related to genetic factors, lifestyle, or unknown environmental exposures. This normal variation makes it difficult to compare means for single individuals.

Although most of our SCE frequencies for smokers fall within the range of all values for nonsmokers, more than 90% of the smokers had a mean frequency greater than the group mean for nonsmokers. As the data were being collected, it became obvious to us that the distribution of SCEs among the lymphocytes in a single individual was not necessarily random. Specifically, we found that some individuals had

normal SCE frequencies in 80% to 95% of their lymphocytes but very high frequencies in the remaining cells. To estimate whether the data were skewed toward cells with high SCE frequencies, we compared the distribution of SCE frequencies among cells of nonsmokers with that of smokers. Figure 4 shows the pooled data from all the individuals in the study. It is evident that smokers

Fig. 3

Lymphocyte sister chromatid exchanges are elevated in groups of cigarette smokers (red) relative to a group of nonsmokers (blue). Each data point represents the SCE frequency in a single person. The horizontal bars represent the mean SCE frequency in each group.

Fig. 4

The distribution of cells with sister chromatid exchanges is positively skewed for smokers in relation to that of nonsmokers. To determine whether cells with an observed high frequency of SCEs were statistically different in the two populations, we pooled and replotted the data for all smokers (red) and nonsmokers (blue) in the form of a histogram. Smokers as a group show a higher proportion of cells with a high SCE frequency than to nonsmokers.

as a group possess a higher proportion of lymphocytes with high SCE frequencies than do nonsmokers; that is, the distribution of SCEs per cell for smokers is positively skewed.

From this observation we developed an alternative, nonparametric statistical procedure to determine whether the proportion of cells with high SCE frequencies is statistically greater in individual smokers than in nonsmokers. We found that an individual with more than 16 SCEs in more than 10% of his lymphocytes was statistically different from the pooled group of nonsmokers (Fig. 5). When the values for individual smokers are compared with their own group mean, 4 of the 52 nonsmokers are "outliers." In contrast, 26 of the 43 smokers are outliers. An additional group of pipe and cigar smokers generally have a normal mean SCE frequency; two of the six individuals in this group are outliers.

The biological significance of lymphocytes with high SCE frequencies remains unknown. Such cells may represent either long-lived lymphocytes that integrate damage during chronic exposure conditions or a highly sensitive subset of lymphocytes that are not competent at repairing DNA lesions, or both. Further experiments are needed to address these hypotheses.

An interesting question for both industrial hygiene and human risk assessment is whether lesions in lymphocytes that produce SCEs persist in the individual or rapidly disappear. To address this question, we worked

with a group of smokers who desired to stop smoking and who had entered a Laboratory-sponsored smoke-enders clinic. We obtained blood samples from these individuals at intervals of four to six weeks for about a year to determine whether their SCE frequencies would decline when they stopped smoking. Some of our data for five subjects are shown in Table 2. Only one individual (subject A) showed a consistent decline in SCE frequency over a seven-month period. The other individuals (B-E) showed no decrease and in some cases even showed a slight increase in SCE frequency, suggesting that SCE-forming lesions can persist after smoking has stopped.

Although our sample was small, the results are consistent with those of other studies of ex-smokers and of occupationally exposed persons. The persistence of high SCE frequencies after cessation of smoking is determined by an individual's biological response to damage, which probably depends on a complex interaction between the effectiveness of his cellular mechanisms for repairing DNA lesions and the kinetics of lymphocyte turnover (lymphocytes have a half life of three months, but some can persist for 20 years). In any case, our studies and others suggest that lesions, once induced in a lymphocyte, can persist for months. Additional studies are needed to determine whether immunological subsets of lymphocytes are unique in their sensitivity to damage or in their repair capacity. By studying a more homogeneous set of lymphocytes, it may be possible to minimize the variations observed among individuals, thereby making the SCE assay even more sensitive.

We are entering a new era of human genetics, marked by fundamental advances, the potential benefits of which are substantial. Yet the ability to measure genetic change in humans is not without controversy. The identification of hypersensitive individuals, the absence of defined consequences for ill health, and fears of tort liability often raise the anxiety

Fig. 5

We used the distribution in Fig. 3 to generate a nonparametric statistical analysis to test the number of cells with a high frequency of SCEs in each smoker against the pooled values for nonsmokers. A lymphocyte with more than 16 SCEs was a statistical "outlier" at the 95% confidence level. The proportion of individuals with a significant number of outlier cells was greatly enhanced in the smoking group. We found that an individual with more than 16 SCEs in more than 10% of his lymphocytes was statistically different from the pooled group of nonsmokers. For example, the highest dot in the figure indicates an individual who has high SCE frequencies in 51% of his cells.

Table 2 Frequencies of sister chromatid exchange in lymphocytes of individuals who stopped smoking.

Months since last cigarette	Mean SCEs/cell per subject				
	A	B	C	D	E
0	10.6	13.7	9.2	11.0	9.3
1	—	11.2	—	9.4	8.1
2	9.9	13.7	9.0	10.6	8.9
3	—	12.5	9.7	11.2	8.0
4	(No measurement made)				
5	9.4	—	10.1	—	9.1
6	9.4	12.4	9.2	10.4	—
7	7.8	—	—	—	12.2
8	—	—	9.9	—	—
9	—	—	—	14.2	12.2

level of workers and employers. It is important, therefore, to emphasize that at present the biological significance of an increased SCE frequency remains unknown and cannot be used to predict any consequences for health. There is persuasive evidence, however, that increased SCE frequencies do reflect exposure to substances that either damage DNA or alter its normal metabolism. The measurement of SCEs in humans can therefore be of use in an industrial hygiene program. For example, a few members of worker populations exposed to hazardous environments could be tested at intervals over a period of time to check for any increase in the number of SCEs. Although these techniques should not supplant current methods based on physical exposure, they can serve as a significant adjunct. More important, they provide what is sometimes absent in physical dosimetry: a measure of biological dose.

Summary

Techniques are available to measure chromosome damage and gene mutation induced in cells while they

are being cultured. Methods are being developed to measure such changes in human beings exposed to potential mutagens or carcinogens. The sister-chromatid-exchange bioassay provides a measure of chromosome change that is easily quantified for human subjects, is correlated with gene mutation, and reflects exposure to environmental and occupational sources. To validate and standardize this bioassay for use on humans exposed to mutagenic substances, we have used it to study exposure in cigarette smokers. Our results and those of others demonstrate the feasibility of using the technique as an industrial hygiene tool for estimating the biological exposure of individuals to potentially noxious substances. □

Key Words: biological dosimetry; industrial hygiene; mutagens; sister chromatid exchange.

Notes and References

1. Sister chromatid exchange was described in detail in an article in *Energy and Technology Review* for October 1978 (UCRL-52000-78-10), p. 1.

Sloshing-Ion Experiments in the TMX-U

Our original Tandem Mirror Experiment (TMX), despite its record-breaking plasma confinement, was unsuitable for direct scaling to the size required for a fusion reactor. Our Tandem Mirror Experiment Upgrade (TMX-U) explores two of the refinements that theory predicts will improve microstability and confinement efficiency: a sloshing-ion distribution and an electron thermal barrier. The experimental verification of sloshing ions has been achieved in the TMX-U.

The Tandem Mirror Experiment Upgrade (TMX-U) is our latest experimental facility for testing the confinement of a plasma by electrostatic and magnetic forces for the fusion energy research program. Construction of the TMX-U facility was completed in late 1981, and (after commissioning the equipment) we were able to perform sloshing-ion experiments during the last half of 1982. The design of the TMX-U is based on that of a smaller tandem mirror machine, the TMX,¹ that we dismantled before building the TMX-U.

The TMX (shown in Fig. 1) consisted of three confining magnets connected in series: one central solenoid joining

two end magnets shaped like the seams in a baseball (this baseball shape induced a magnetic field, B , that was weakest at its center and therefore suited to confine a plasma). The minimum- B baseball magnets and the solenoid magnet enhanced each other's

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Fig. 1

Schematic drawing of the TMX machine, showing the magnet coils, the neutral-beam injectors (all aimed at 90° to the machine axis), and the plasma bundle (magenta). The TMX was only 7 m long, whereas the TMX-U is 14 m long.

This innovation should produce a large electrostatic-potential gradient in the end plugs, even with less powerful magnetic fields and lower neutral-beam energies.

confinement properties and enabled the combination to achieve plasma densities and confinement times far beyond what either magnet type could attain alone.

An important feature of the TMX-U is the injection of high-energy neutral atoms, both to maintain the density of the plasma (by replacing losses) and to heat the plasma (by exchanging hot ions for cold ones). The injected neutral particles (produced first as ions and subsequently accelerated and neutralized within structures known as neutral beams) interact with the plasma through ionization and charge-exchange collisions. The energy of the plasma can be increased both by ionization and by charge exchange between neutral particles in the beams and electrons and ions in the plasma; however, the number of plasma ions can be increased only through ionization. Charge-exchange collisions begin and end with an ion and a neutral atom exchanging electrons; hence, there is no net increase in ion density.

In the TMX, the injected neutral-atom beams were oriented at right angles to the machine axis. The resulting plasma column had a density maximum and an associated potential maximum at each of its two end plugs; together, the central-cell potential well and the end-plug magnets helped plasma ions within the central solenoid.

The TMX design, however, was unsuitable for scaling directly to reactor size. Both the magnetic fields and the neutral-beam energies required are well beyond present-day technology. The TMX-U explores two of the refinements that theory² predicts will improve the plasma's microstability and confinement efficiency. These two important new features in the TMX-U are thermal barriers in the end plugs and changes in the angles at which neutral beams are injected.

The thermal barriers isolate the electrons in the end plugs from those in the central cell, making it possible to heat the end-plug electrons independently with tuned microwaves. This innovation should produce a large electrostatic-potential gradient in the end plugs, even with less powerful magnetic fields and lower neutral-beam energies.

The second of the two new TMX-U features, oblique-angle beam injection, is expected to improve plasma microstability (a measure of the resilience of the velocity distribution of the ions and electrons to spontaneous, self-induced, oscillating electric fields). Ions derived from obliquely injected neutral beams should improve the density distribution in the end plugs by tending to slosh back and forth in the magnetic field. When applied to plasma ions, the word "sloshing" refers to a collective motion of ions within the confining magnetic field (the "magnetic mirror"). The ions spend much more time at the boundaries of their movements, where they are moving slowly, than they do in the center, where they are moving fast. This makes the plasma pressure greatest at the ions' turning points nearer the magnetic mirror than at the center (see Fig. 2).

To understand better how sloshing ions act, imagine two or three balls rolling in a bowl. The balls' velocity is maximal at the bottom of the bowl and nearly zero as they turn at the edge of the bowl and begin to roll in the opposite direction. Furthermore, the balls crowd each other at the turns, where they move slowly, and separate as they speed up, in much the same way as cars on a freeway do. Ions sloshing in a plasma behave similarly, their density being related to their speed and location.

One of our major objectives in building the TMX-U was to produce sloshing ions. A conventional plasma distribution is most dense in the midplane of the end plugs, but the distribution of sloshing-ion plasma is minimal at the end-plug midplane; this provides the minimal electrostatic potential required for a thermal-barrier end plug. The distribution of a sloshing-ion plasma should be less vulnerable to loss-cone instabilities. This article describes the experimental verification of sloshing ions in the TMX-U.

TMX-U Experimental Facility

The TMX-U is the first experimental facility designed to test the end-plug configuration that will probably be used in a future tandem-mirror fusion reactor, that is, an end plug with thermal barriers. The purpose of the TMX-U is to confirm the thermal-

barrier concept (discussed below) and to give us experience in generating and controlling thermal barriers. This experience will be useful when we begin operating the next major test facility in our mirror-fusion program, the Mirror Fusion Test Facility (MFTF-B), which is scheduled to be operational in fiscal year 1986.¹ The MFTF-B will test the scientific feasibility of a tandem-mirror reactor with thermal barriers, as well as demonstrate the technologies necessary to produce the core plasma in a reactor (for example, superconducting magnets, 30-s neutral beams, and cryopanel surfaces cooled with liquid helium).

Figure 3 illustrates the TMX-U magnet-coil arrangement, the location and orientation of the neutral-atom beams, and the plasma bundle. The plasma's cross-sectional area changes inversely with the magnitude of the magnetic field produced by the coil set. The central cell has a magnetic-field strength of 0.3 T, and each end-plug magnet set generates a 2-T quadrupole-mirror field having a 4:1 mirror ratio, B_m/B_0 . The 4:1 mirror ratio,

Fig. 2

Plots of the end-plug magnetic field strength (red), the normal ion-density profile characteristic of the TMX (yellow), and the sloshing-ion distribution (blue) characteristic of the TMX-U end plug as a function of axial position. The sloshing-ion distribution can result from injection of neutral beams either perpendicular to the axis at a point between the midplane (B_0) and the mirror (B_m) or through the center at an angle (e.g., 45°) to the midplane.

Fig. 3

Schematic drawing of the TMX-U machine, showing the new magnet coils, the neutral-beam injectors (all aimed at oblique angles to the machine axis), and the plasma bundle (magenta).

(a)

Fig. 4

The TMX-U in artist's conception and in reality. (a) Cutaway to show the magnet coils at one end. (b) Recent photograph of the TMX-U facility. The rectangular box in the foreground accommodates the plasma's vertically oriented end fan. Diagnostic instruments and neutral-beam sources are attached to the vacuum vessel. (The artist's drawing views the side of the vessel, and the photograph views the vessel from its end.)

compared to the earlier TMX value of 2:1, is required to confine the sloshing-ion distribution. Ions and electrons with a velocity vector at the midplane of the end plug with an angle $\theta < \theta_m$, with respect to the magnetic axis, are lost in a transit time. The angle in velocity space, θ_m (given by $\sin^2 \theta_m = B_p/B_m$), is called the "loss cone" because ions or electrons entering it will rapidly be lost.

Neutral beams are defined in terms of their angle of injection, axial position, and purpose. The end-plug neutral beams aimed at approximately 47° to the magnetic axis create the sloshing ions (hence, they are called sloshing beams). The beams directed into the central cell at 65° provide power to heat and fuel the central-cell ions; they are called central-cell beams. The end-plug beams aimed at 18° are for additional charge-exchange "pumping" of low-temperature ions that become electrostatically trapped within the density peaks of the sloshing ions (Fig. 2); these beams are known as pumping beams. They are injected axially at an angle less than the loss-cone angle θ_m , which, for $B_p/B_m = 1/4$, is 30° . The ions trapped within the density peaks would eventually fill in the density minimum were it not for the collisions between them and the neutral atoms from the pumping beam. The trapped ion becomes a neutral atom and the injected pumping-beam atom becomes a positive ion when the former captures an electron from the beam atom. The trapped ion becomes neutral and leaves the magnetic field region, while the pumping-beam atom becomes ionized and escapes into the central cell because its path is within the end-plug loss cone.

Figure 4 shows the vacuum vessel of the TMX-U. In the artist's rendering (Fig. 4a), neutral-beam ports and their oblique entry angles are clearly discernible; in the recent photograph of the actual vessel (Fig. 4b), the diagnostic instruments and peripheral machinery on the TMX-U nearly obscure the beam ports.

The vacuum chamber that houses the entire apparatus contains titanium-

The TMX-U is the first experimental facility designed to test the end-plug configuration that will probably be used in a future tandem-mirror fusion reactor, that is, an end plug with thermal barriers.

coated surfaces (hollow panels filled with liquid nitrogen) that pump out cold hydrogen gas (if left in the chamber, the hydrogen gas would contaminate the plasma by unwanted charge exchanges). The 540 square metres of surface in the TMX-U are covered with titanium atoms sublimated from hot titanium wires that function as getters. This surface can pump hydrogen gas at a rate of six million litres per second.

Different operating modes can give different plasma-density distributions in tandem-mirror machines. Figure 5 illustrates the density distributions to

be expected in three different operating modes. The first is the original mode of the TMX, which gives a density peak in the center of the end plug. The second is the TMX-U's initial operating mode, in which we verified the sloshing-ion distribution; thermal barriers (depressions in the plasma's electrostatic potential, ϕ , that separate electrons in the central cell from those in the end cells) were not used. The third, which will be tested in the TMX-U, is a mode using thermal barriers; this last mode is the one proposed for use in a future tandem-mirror reactor.

Fig. 5

Operating modes of tandem-mirror machines. The second column indicates plasma potentials in proportion to plasma densities. The plasma densities are shown in black. The blue shape indicates the profile of the magnetic field, which is the same in all three operating modes. (a) The basic tandem-mirror mode, characteristic of the TMX. (b) The tandem-mirror mode with sloshing ions, achieved in the TMX-U. The plasma density now has a depression at the center of the end-plug mirror. (c) The tandem-mirror mode with electron-cyclotron resonance heating (ECRH) in conjunction with thermal barriers, planned for future TMX-U experiments. In the notation used here, ϕ is electrostatic potential, T_{ap} is the end-plug electron temperature, T_{ec} is the central-cell electron temperature, T_e is the electron temperature when $T_{ap} = T_{ec}$, n_p is end-plug electron density, n_c is central-cell electron density, and n_b is the potential-confined electron density at the minimum potential within the thermal-barrier end cell.

The main function of a thermal barrier is to provide thermal insulation for the electrons in the end plug from those in the central cell. The thermal barrier is located at the point where ϕ is at a minimum (see Fig. 5). This depression in the plasma potential serves as an electrostatic-potential barrier for the negatively charged electrons. The end-plug electrons can therefore be heated by means of tuned microwave energy (electron-cyclotron resonance heating, or ECRH) to temperatures greater than that of the central-cell electrons. This, in turn, expedites the end-plug electrons' escape from the plasma, raising the local plasma potential beyond the values obtained in the TMX. In the TMX experiments, plasma potential depended entirely on differences between the electron densities of the central cell and of the end plugs.

For each operating mode, Fig. 5 also indicates the power input to the plasma, the theoretical expression for the central-cell ion potential (ϕ_c), and the source of low-temperature ions that help provide microstability against leakage out the loss cone of energetic plasma ions injected into the end plugs by neutral beams. One-half of the axial magnetic field profile (B), common to all three tandem-mirror modes, is shown, together with the individual axial potential profiles (ϕ) of each mode. The ion potential in the central cell augments the magnetic-mirror confinement of the central-cell ions by the exponential factor $\exp(\phi_c/T_c)$, where T_c is the temperature of the central-cell ions.

In the TMX, end-plug neutral beams were injected at 90° to the magnetic field lines to generate a higher plasma density in the end plugs (n_p) than in the central cell (n_c). The central-cell ion confining potential was determined by the Boltzmann relation,

$$\phi_c = T_c \ln n_p/n_c$$

and microstability was maintained by losses of central-cell ions.

In the initial sloshing-ion mode of the TMX-U, neutral beams are injected in the end plugs at 47° to the field

lines. In this case, the ions slosh back and forth, generating density peaks at their turning points—at a distance from the magnetic-field minimum at the midplane of the end plug. As a result, the axial potential profile has a dip at the midplane which can electrostatically confine low-energy ions. (As in the original tandem mode, central-cell ion losses continue to provide stability.) A further benefit of oblique-angle beam injection is that it reduces the temperature-anisotropy drive of the Alfvén ion-cyclotron (AIC) mode,⁴ another ion-loss mechanism that was present in the TMX.

In future thermal-barrier experiments in the TMX-U, we will increase the ion-confining electrostatic potential by microwave heating (ECRH). Heating the electrons outside the thermal barriers increases the temperature of end-plug electrons (T_{ep}) above that of central-cell electrons (T_{cc}). We then expect to obtain ion microstability without having to rely on central-cell ion losses because electrostatically trapped ions and central-cell passing ions will be present.

Central-cell passing ions are ions that are reflected by the outside potential peak of the thermal-barrier end plug (see Fig. 5). The passing-ion density takes the place of the central-cell ion loss density, which, because of its poor confinement, was an inefficient source of low-energy ions for microstability. Using passing ions for microstability eliminates the requirement that the central-cell ion losses must exceed a minimum value set by end-plug microstability. Therefore, longer central-cell confinement times are theoretically possible.

Experimental Verification of the Sloshing-Ion Distribution

The TMX-U now has sloshing ions in both end plugs. However, full TMX-U operation, which includes thermal barriers, requires not only sloshing ions (created by neutral beams injected at skew angles less than 90°),

but pumping beams and ECRH as well. In our initial tests on the TMX-U, we created sloshing-ion plasmas without pumping beams and with a minimum of ECRH power.⁵ Even without these aids, the sloshing-ion density in the TMX-U was more than five times larger than sloshing-ion plasmas achieved in other experiments.^{6,7}

Many parts of the TMX-U's initial array of plasma diagnostic equipment (Fig. 6) helped us identify sloshing ions.⁵ Secondary-emission detectors (SEDs) provided the main data, but important details were filled in by resistance-probe and solid-state-probe measurements of ion energies, diamagnetic-loop measurements of the perpendicular plasma pressure (related to plasma density), and microwave-interferometer measurements of electron density.

The SEDs measure the current of electrons emitted from an active surface when struck by a neutral particle. Angular arrays of SEDs on each end plug determined the flux of energetic neutral particles leaving the plasma region at various angles to the magnetic field.⁸ The neutral particles we measured resulted from charge

exchange between plasma ions and cold gas or neutral-beam atoms.

Figure 7a shows the measured charge-exchange flux of neutral particles (in relative units) as a function of angle for the east end plug at a particular time during an experimental plasma shot. The peak in the experimentally measured flux signal near the injection angle is indicative of a sloshing-ion distribution. Note that no energetic ions are measured at angles less than 30° (the loss-cone angle for the 4:1 mirror ratio of the end plug). This is to be expected; any end-plug ion scattered into this angular range escapes almost immediately.

Figure 7a also shows the result of Fokker-Planck calculations² done with a computer code that models sloshing-ion distributions. The agreement between the SED data and the calculation in the vicinity of the peak indicates that the angular width of the sloshing-ion signal can be explained by ion-ion collisions and curvature in the magnetic field lines. However, Fokker-Planck calculations have not as yet completely explained the discrepancy between code results and experimental data at angles greater than 60° . Measurements with solid-state and

Fig. 6

The initial array of plasma diagnostic equipment on the TMX-U. Measurements required to define the parameters of the plasma were extremely complex.

resistance probes indicate that the SED signal at 47° comes from magnetically confined ions with an energy of about 6000 eV.

The presence of a sloshing-ion distribution is further substantiated by an axial array of diamagnetic loops. Figure 7b shows the axial magnetic-field profile for one-half of an end plug. The diamagnetic loop data, in agreement with the code calculations, indicate a higher perpendicular pressure near the sloshing-ion turning point.

Figure 7c is the axial density profile of the sloshing ions, as it is calculated from measurements using the angular array of charge-exchange detectors. Microwave interferometers measure electron densities at the end-plug midplane and near the turning point of the sloshing ions. From this measurement, we can also deduce that the midplane has, in addition to sloshing ions, a comparable density of low-energy ions.

The TMX-U has, therefore, achieved densities in the mid- 10^{12}-cm^{-3} range, as the proposed thermal-barrier operating mode will require. The skewed

injection angle of 47° results in a hot-ion, end-cell plasma 2 m long, about five times longer than the plasmas the TMX achieved with 90° injection angles. Furthermore, we have generated a sloshing-ion density maximum at a distance from the midplane, as the thermal-barrier mode requires.

Sloshing-Ion Microstability

To evaluate the microstability of the sloshing-ion distribution for the TMX-U, we measured ion-cyclotron fluctuations using electrostatic radio-frequency probes in each end plug and in the central cell. These probe measurements showed that the level of self-induced fluctuations of electric fields in the TMX-U were a factor of three less than that in the TMX, without observable degradation of plasma confinement. By this measure, the TMX-U is three times as microstable as the TMX.

Without sloshing ions, the TMX-U would, in theory, be more vulnerable to microinstability than the TMX was because it has sharper radial-density gradients and longer end plugs. With sloshing ions, however, the fluctuation

Fig. 7

Measurements of quantities representative of sloshing ions compared with the Fokker-Planck calculations (yellow) for (a) angular distribution (SED measurements of fast neutral particles); (b) axial pressure distribution (diamagnetic loop measurements); and (c) axial density distribution (calculated from SED data).

For the first time in a magnetic-mirror machine driven by neutral beams, there were no discernible fluctuations with the ion-cyclotron frequency of the end-plug midplane.

amplitudes of the self-induced, oscillating electrical fields in the TMX-U are smaller than those in the TMX (less than 1 V when measured at a radius equal to twice the plasma radius). Furthermore, the fluctuations in the TMX-U are characteristic of a loss-cone-driven mode rather than the AIC-driven mode measured in the TMX.⁴ The frequency of rf fluctuations in the TMX-U reflects that of the ion-cyclotron frequency outside the sloshing-ion density peak, where warm ions would not be electrostatically confined.

Compared with the AIC oscillations observed in the TMX, the loss-cone-driven mode of the TMX-U has a larger bandwidth, a smaller wavelength, and essentially no bursting (low-frequency amplitude modulation of the rf fluctuations). A very important difference is that, in the TMX-U, the fluctuations neither propagate to the central cell nor appear to interact strongly with the central-cell ions. All these characteristics agree qualitatively with theory.

Further evidence that sloshing ions improve microstability can be found in the energy spectra of central-cell ions that escape through the end plugs to the end walls of the vacuum vessel. Figure 8 compares the energy spectra of escaping ions in the TMX and the TMX-U, each operating at a 400-V potential so that the loss-cone drive is comparable. In the TMX, the escaping, 75-eV central-cell ions were heated to 810 eV by the fluctuations as they passed through the plug, whereas in the TMX-U, the 100-eV ions were heated to only 110 eV. In the TMX-U, the undesirable, spontaneous rf heating associated with microinstabilities is hardly measurable.

Conclusions

Sloshing ions were successfully generated in the TMX-U. Ion-velocity distributions were measured to have an angular distribution peaked near the neutral beams injected at 47°, which agreed with theoretical Fokker-Planck descriptions of sloshing-ion activity. The hot-ion fraction exceeded 50%, and

the hot, sloshing-ion plasma was 2 m long, approaching within a factor of two the end-plug plasma length required for proposed, full-scale tandem mirror-reactor end cells. An ion-density maximum at a distance from the midplane was established at values consistent with requirements of future thermal-barrier experiments in the TMX-U.

We observed no degradation in ion confinement attributable to microinstabilities, and unwanted heating of escaping central-cell ions was negligible. For the first time in a magnetic-mirror machine driven by neutral beams, there were no discernible fluctuations with the ion-cyclotron frequency of the end-plug midplane. The low-amplitude fluctuations that we did observe had the characteristics predicted by theory for sloshing-ion plasmas. □

Key Words: Alfvén ion-cyclotron oscillation; Fokker-Planck; magnetic fusion energy (MFE); MFTF-B; microinstability; plasma density distribution; sloshing ion; tandem mirror; Tandem Mirror Experiment (TMX); Tandem Mirror Experiment Upgrade (TMX-U); thermal barrier.

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Fig. 8

Comparison of energy spectra of central-cell ions escaping through the end plugs, measured in the TMX and the TMX-U (both operating at 400-V potential for comparable loss-cone drive). The ion energy, directed motion from potential energy, and thermal motion from kinetic (temperature) energy, must equal or exceed the ion repeller voltage in order that the ion current be detected. Independent measurements established that the temperature of central-cell ions was 75 eV in the TMX and 100 eV in the TMX-U. In the TMX, these 75-eV ions became 810-eV ions upon traversing the end plug (their intensity remained above 36.8% i.e., one (1/e-folding) factor of its original value all the way out to 1210 V, which is 810 V over the operating potential), indicating a substantial amount of undesirable rf heating. In the TMX-U, rf heating added only a barely discernable 10 eV to the 100-eV temperature of the central-cell ions.

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8. This detector array consists of a set of negatively biased targets, each surrounded by a coaxial collector at ground potential with a collimator that admits particles from only one general direction. An energetic particle striking any one of the targets produces an electron that flows to the collector. Measurements of the current in each circuit determine the angular extent of the energetic particle flux.

Aluminum-Air Battery Development: Toward an Electric Car

In preparation for the inevitable decline in petroleum supply, we are developing the aluminum-air battery as a convenient and economical way to extend the energy base available for automotive propulsion. This technology will soon be transferred to private industry for further development of the battery for vehicular and other applications.

The development of transportation alternatives for the closing decades of the petroleum era is one of the most necessary and challenging efforts of our time. According to the best available estimates, world oil production will peak and begin an irreversible decline sometime near the end of this century. The problem of oil supply in the West will be compounded by geopolitical

forces, international trade imbalances, and the concentration of oil in potentially hostile or unstable countries. The intensity of the problem will fluctuate, but the eventual exhaustion of conventional sources of petroleum is inevitable.

One possible alternative for transportation in the future is a battery-driven vehicle that draws upon energy as such, not just a particular (fossil) form of energy. Such a vehicle could ease a nation's demand for petroleum and for the massive synthesis of liquid

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fuels from oil shale and coal. In the long run, it might efficiently exploit the broadest possible primary energy base through the common medium of electricity.

Much effort has been devoted to developing rechargeable batteries for electric vehicles in the last 15 years. Projects, supported by public and private funds, have flourished here and abroad. However, these efforts have not produced a single indisputably viable battery system to replace the internal-combustion engine (ICE) in private automobiles. The life-cycle costs of secondary batteries for electric vehicles now far exceed the costs of ICEs. At the same time, the short range or poor acceleration of electric vehicles, as well as the many hours required for recharging batteries, limit them to such uses as delivery vans, taxis, and urban commuter vehicles.

The aluminum-air battery is being developed, at the Laboratory and elsewhere, because its high specific energy ($300 \text{ W} \cdot \text{h/kg}$) and power (150 to 200 W/kg) promise a driving range and acceleration comparable to those of today's automobiles. Another positive feature of the aluminum-air battery is that it can be rapidly refueled by the addition of water and aluminum (see Fig. 1). It is the only known battery that

eventually may provide an electric vehicle as useful as today's gasoline-powered automobile.¹ (See the box on p. 27 for a description of the chemical basis of the battery.)

In 1979, we began developing a refuelable aluminum-air battery for electric vehicles. Prior to that time, we had explored other electrochemical fuels (lithium and calcium, in addition to aluminum). Since then, we have led a multifaceted program, combining both government and corporate research, to develop and test critical components and processes of the battery and to determine its technical and economic feasibility.

We are now in the process of transferring this technology into the private sector and of selecting a prime subcontractor to continue developing the battery for vehicular and other applications. LLNL will continue to manage the program for the Department of Energy, working within DOE guidelines to set major milestones and funding levels and to monitor and interpret progress. In addition, the Laboratory will fund and convene a committee to review the battery program, to judge the quality of its work, and to recommend research for it to undertake. We will also continue our in-house research on the fundamental

Fig. 1

Fuel cycles of transportation systems based on aluminum and on gasoline. The aluminum-air battery releases electrical energy by oxidizing aluminum with air (in the presence of tap water and a catalyst). The solid reaction product is periodically removed from the vehicle and recycled. Since the plates last about 1600 to 3200 km in the battery, a fixed amount of aluminum could be used to distribute energy from any available source of electricity. The economics and energy balance of this use of aluminum have been discussed in earlier issues of this journal.²

scientific and engineering aspects of the aluminum-air battery.

When we began work on this project, we set ourselves the following tasks: to investigate the relevant electrochemical and chemical basis of the battery; to develop an understanding of the economics and energy balance of a transportation system based on aluminum; and to design cells capable of being rapidly refueled.

In late 1980, we reported an important advance in our research, the operation of large laboratory cells (non-refuelable) with simple crystallizers to establish compatibility of the basic processes.² At the same time, we defined four critical needs that would have to be filled: cells capable of mechanical refueling, a practical crystallization process, an air cathode of sufficient longevity, and anode alloys of low cost and high efficiency.³ Since that time, some of these concepts have become realities, and a firm technological basis has been established on which to build the next major phase of the program: the development of a full-scale prototype electric vehicle battery.

Since 1980, we have made the following advances on the aluminum-air battery:

- Four different refuelable cell concepts have been formulated and experimentally evaluated in parallel projects. The best of them (the aluminum-wedge cell depicted in the box on p. 27 and described further below) was chosen for use in our future prototype battery because of its unique ability to use all the aluminum fuel introduced and because of the relative simplicity of its design.
- Six individual cells of two of these designs have been ganged together to form integrated, multicell modules—the basic building block of a battery. While many battery concepts fail at this stage of development, the aluminum-air multicell modules conserved or improved their single-cell performance.
- Macrocyclic catalysts have been developed as a low-cost replacement

for the platinum in earlier air cathodes. These catalysts not only obviate the use of expensive noble metals but also improve the life of the air electrodes to more than 1000 cycles of a simulated vehicle trip. (Fifteen hundred cycles are needed for a goal of a two-year air-cathode life.)

- The crystallization of hydrargillite has been investigated over the range of conditions accessible to a vehicle, and an understanding of the kinetic and chemical balance has been developed as an aid in the engineering design of practical units.

A firm technological basis has been established on which to build the next major phase of the program: the development of a full-scale prototype electric vehicle battery.

- At the start of the program, we tested cells with aluminum alloy anodes based on expensive superpure metal. Since then, high-performance alloys based on aluminum of commercial purity have been developed and their production cost accurately estimated. This is a first, major step in the direction of establishing the economic feasibility of this concept.

- We have operated a large-scale cell in conjunction with a crystallizer to establish the compatibility of the distinct processes of aluminum dissolution and aluminum-trihydroxide precipitation.

- We are currently integrating a stack of prototype aluminum-wedge cells with a crystallizer to investigate the behavior of a scalable engineering unit of a vehicle battery. The experimental program provided

information we used to make an advanced engineering design of a vehicle battery and to refine our earlier estimates of energy consumption and other economic costs.

Early in the program, we realized that we could treat the requirement for efficient, cost-effective electrodes⁴ as one research problem and (up to a point) separate it from the problem of developing the recrystallization process and the various hardware subunits the battery would require. Since the critical question appeared to be the technical feasibility of a refuelable battery with high specific power and energy, we chose to concentrate on this area.

Accordingly, the program has emphasized the development of rapidly refuelable cells and cell stacks capable of complete anode utilization and their integration with a crystallizer. From this point, however, further engineering development will require parallel advances in anode efficiency and air cathode reliability.

Developing the Refuelable Cell

In the first refuelable cells designed expressly for vehicles, we used

replaceable anode modules. These consisted of plates of aluminum soldered (or bonded with conductive cement) to copper-clad epoxy boards (Fig. 2). The air cathode in these first cells was mounted on a flexible diaphragm so that air pressure would hold it against the anode; plastic ribs on the cathode maintained constant separation between the electrodes. While this design allowed rapid refueling, it was not optimal for commercial vehicles because of the high fabrication cost associated with some of its features (the fixed electrical contact and the need to protect the contact from the corrosive electrolyte).⁵

Under a subcontract, Lockheed Missiles and Space Company invented a "solution-side current collector" for us. In Lockheed's design, the plastic ribs on the cathode and the soldered contacts on the anode were eliminated in favor of a metal grid that provides electrical contact to the anode when it is submerged in electrolyte (Fig. 2). The grid, if carefully designed, effectively eliminates the parasitic corrosion that normally occurs near the junction of dissimilar metals.⁶

Unfortunately, the Laboratory's and Lockheed's first designs shared a fundamental drawback: they could not use all the aluminum fuel introduced into the cell. As the anode dwindled, it became thin, weak, and ragged. It had to be removed before it disintegrated, while about 20% of it remained unconsumed.

We solved this problem by developing a wedge-shaped cell, shown in Fig. 3. Although this type of cell was first proposed for saline electrolytes,⁷ our use of it called for a caustic electrolyte; this made it necessary to revise the design of the current collector. The Lockheed grid, with its point contacts, was replaced with parallel, triangular-bar contacts of tin-plated copper. Now, as the aluminum-slab anode dissolves at the surfaces next to the cathode, it slides continuously into the cell, gradually assuming the wedge shape.

The wedge cell has other advantages that help make it our preferred design

Fig. 2

One of our earlier designs of an experimental six-cell battery module, opened to show flat anodes and movable air cathodes. Air pressure was used to keep the cathode-spacer assemblies pressed against the anodes as the latter dissolved away. Aluminum anode plates were soldered to flat copper-epoxy laminate backing for low-resistance electrical connection. In contrast to the battery design with a wedge-shaped cell, this battery would have to be disassembled each time the anodes needed replacing.

for a vehicle battery. It can be partially recharged by adding plates of different heights to the cell; this allows the vehicle's fuel supply to be "topped off" and the cells' energy capacities to be equalized (the central cells in a stack run warmer than those at the ends and hence consume their anodes faster). The cell's simple design has no moving or flexing mechanical components. The air electrodes are contained in inexpensive and removeable cassettes, and they can be replaced individually as they wear out, which offers major savings in stack cost.

Perhaps most significant is the way this cell is refueled. Adding metal plates through a slot in a dry chamber above the cell is easy and safe, since it is done at a distance from the corrosive

fluid and the fragile air cathodes. The battery might well be refueled by the vehicle's owner in his own garage.

Furthermore, a year's supply of aluminum plates would occupy a space of about 0.2 m^3 and, unlike stored gasoline, for instance, would represent no hazard. A year's supply of aluminum could be delivered at one time, like home heating oil, guaranteeing the owner independence from intermittent shortages. The reaction product could be stored in containers the size of trash cans for monthly collection. From the standpoint of the transportation system, home refueling would eliminate the need for a complete network of special service stations to accommodate even the first few customers.

Fig. 3

Two views of our prototype wedge-shaped cell. (a) Cutaway drawing showing individually replaceable air-cathode cassettes meeting at an angle of about 3 to 6°. Electrical contact to the aluminum anode (originally a flat slab but etched by the in-cell process to a wedge shape as it sank into the cell) is by means of copper bars with triangular cross sections immersed in the electrolyte (no soldering is required). New anode material feeds in from above as needed. (b) Exterior view (model). The active area of the anode is 625 cm^2 . An electric-vehicle battery delivering 40 kW peak current would need about 100 such cells.

Integrating Cells and Crystallizer

A fixed volume of electrolyte becomes supersaturated when an aluminum anode is dissolved in it; however, the aluminate concentration in the electrolyte can be stabilized by continually removing the excess aluminate with a crystallizer (see Fig. 4). The supersaturated electrolyte is metastable and will decompose into solid aluminum trihydroxide if brought into contact with seed particles in a crystallizer. The crystallizer contains a fixed mass of seed particles and permits a slow exchange of electrolyte between the crystallizer tank and the cell's closed electrolyte circuit.

We have operated a large-scale cell in conjunction with a crystallizer to establish the compatibility of the distinct processes of aluminum dissolution and aluminum trihydroxide precipitation. We are now attempting to integrate a number of engineered, full-scale cells with a crystallizer and to operate this combination under conditions simulating service in a vehicle. Unlike our earlier work, this experimental cell-and-crystallizer system uses only processes that could be scaled up for use in a vehicle battery. We expect to demonstrate by these experiments that the aluminum-air battery is indeed practical for automotive propulsion. This work will also provide a technology base on which advanced laboratory and vehicular prototypes of the battery can be developed.

Fig. 4

Effect of a crystallizer used to stabilize the aluminate concentration in the electrolyte in an aluminum-air battery. When the crystallizer is not used, the concentration of sodium aluminate in the cell builds up steadily. With circulation through the crystallizer (begun here at 90 min), the concentration stabilizes. When the cell ceases to deliver current (240 min here), the crystallizer continues to reduce the concentration. The solution is supersaturated at aluminate concentrations above 0.95 M.

Electrode Developments

The life expectancy and efficiency of the air electrode are major determinants of its economic feasibility. We have developed test procedures for evaluating candidate electrodes over vehicular duty cycles. The test cycles consist of a series of electrical current plateaus (representing such conditions as cruising and accelerating) followed by a period on open circuit in a cell without electrolyte (the condition of a battery resting overnight).

To meet our goal of a two-year life expectancy, an air electrode would have to sustain 1500 cycles over a period of 500 h operating time. Today, we routinely obtain lifetimes of 500 to 1000 cycles. Electrodes fail largely from the cumulative effects of corrosion processes occurring in the first few hours following the resting phase of each cycle.

At the start of this program, the only catalyst we knew of that could provide the high discharge rates required of a vehicle battery was platinum (loaded at a rate of 1 to 3 mg/cm² of air-electrode area). Platinum is too expensive and too scarce to supply the demands of any sizable fleet of electric cars. Under subcontract, Diamond Shamrock Inc. and associates at Case Western Reserve University developed and tested, under driving conditions, air electrodes catalyzed with large-ringed hydrocarbon molecules called macrocyclic complexes (chlorophyll is probably the best-known example of such a complex). One complex, cobalt tetramethoxyphenylporphyrin (CoTMPP), worked better than the platinumized electrode for most of its life of more than 1000 driving cycles. This work continues toward the development of a cheap and plentiful substitute for platinum catalysts.

Cheaper Aluminum Alloys

There is also progress in the development of low-cost aluminum alloys. Aluminum of commercial purity, such as that used in cans or foil, contains from 400 to 5000 ppm of iron, which cuts anode efficiency drastically

Chemical Basis of the Battery

An aluminum-air battery has two major components: a stack of galvanic cells that produces the electricity and a crystallizer that converts the soluble reaction products into a granular, recyclable form. The figure shows schematically one promising configuration. In the cell stack, aluminum, water, and atmospheric oxygen combine to yield electricity and a supersaturated solution of caustic aluminate:

The air cathode (which makes the reaction possible by scavenging oxygen from the air) is a porous, sintered structure composed of carbon particles, Teflon wet proofing, an oxygen-reduction catalyst (such as platinum), and a conductive wire screen.

The central feature of this cell (our latest design) is the wedge-shaped aluminum anode between the two air-cathode cassettes. As the reaction proceeds, the aluminum anode dissolves on the faces next to the cathodes and, still in wedge form, gradually slides into the cell. Additional fuel plates, stacked above the anode, feed themselves in and gradually assume a wedge shape as they are

consumed. In this manner, all of the aluminum fuel can be used to produce electricity. Refueling is accomplished simply by adding more aluminum plates to a chamber above the cell and fresh water to a tank.

The reaction product, caustic aluminate, is carried by the flowing electrolyte into the second component of the battery, a crystallizer, where it decomposes to yield sodium hydroxide and aluminum trihydroxide (hydrargillite):

The solid, granular hydrargillite is essentially identical to the feedstock used by the aluminum industry, which suggests the possibility of economical recycling.

The amount of energy the cell yields depends strongly on the exact composition of the aluminum anode and the way the plates are formed. Common scrap aluminum is unsuitable because of its alloyed impurities, and pure aluminum reacts too slowly for applications requiring high power. To provide the necessary energy and power, the aluminum fuel must be alloyed with certain metals (while others are carefully excluded) and specially processed.

and generates large amounts of unwanted hydrogen. (Model anodes for our hardware development were based on superpure aluminum, usually alloyed with gallium to increase efficiency and rate of discharge.) Under subcontract, Reynolds Aluminum developed a potential substitute containing manganese, which forms an iron-manganese intermetallic compound that greatly reduces hydrogen evolution. The resulting anodes are 85% as efficient as the superpure aluminum-gallium anodes and only slightly more expensive than aluminum of commercial purity.

Major Problem Areas

We have verified that the essential processes and components of an aluminum-air battery are technically feasible. Nonetheless, a number of vexing problems remain before a prototype vehicle can be fabricated and tested, even if the expensive model anodes are used. One problem is to engineer a practical component for crystallizing, classifying, washing, and removing the hydrargillite product on board a vehicle, while taking into account the vehicle's mass and volume constraints.

Another problem is cathode reliability. An air cathode with a 99% probability of surviving a road test is not good enough; it makes the survival probability of a ten-cell module only 90%, and of a 100-cell vehicle battery about 35%, even if the electrodes do not interact. (If they do, so much the worse.) This problem is diminished somewhat by the ability to sense incipient failure in individual cathodes and to replace them, which was one of our motives for designing the cassette described above.

Another major problem is the chemical balance of the battery. Problems in battery efficiency and operating stability may arise from the buildup of trace impurities in the electrolyte and on the electrodes or from the exhaustion of such materials as corrosion inhibitors and bonding agents. Although the behavior of the battery's main chemical constituents is

known, we must learn how to manage the sources and sinks of minor constituents.

We do not expect any of these problems, given appropriate attention, to deter the orderly development and testing of a vehicular prototype battery.

Making the battery economically competitive is an entirely different matter; this depends most strongly on the energy efficiency and manufacturing cost of the aluminum-alloy plate. Although the Reynolds alloy of aluminum, gallium, iron, and manganese is a good start, we need a 30% improvement in the efficiency/cost ratio to meet our goal of less than 6¢/km. (Gasoline at \$1.25/gallon for a 25-mpg car costs 3¢/km.) It is also important, as we have said, to improve the life expectancy, reliability, and manufacturability of the air electrode.

Battery Engineering Design

After investigating both cell and crystallizer processes in the laboratory, we designed a full-scale vehicle battery and simulated its operation, under various driving conditions, on a computer.⁴⁰ Although this design is based on an earlier one that used parallel plates, much of the design can be extended to the wedge configuration.

The aluminum-air battery system is much simpler than an internal combustion engine but more complex than the familiar lead-acid storage battery. In addition to the cell stack and crystallizer, it includes several subcomponents: storage containers for water and hydrargillite precipitate, pumps to circulate the air and the electrolyte and to control the flow of water, air filters, a moisture-enthalpy exchanger, and an auxiliary battery for starting and control. Figure 5 is a flow diagram of a candidate design, indicating the basic interconnections of the system's components. Figure 6 is a drawing of how the parts of such a battery might look in three dimensions.

In this design, the air-flow system serves two functions. It supplies pressurized atmospheric air to the

cathodes, where some of the oxygen is consumed. The spent air then powers a bubble pump to circulate the electrolyte.

Even here, subsidiary processes are taking place. To prolong the life of the air cathodes, the air is first filtered to remove dust and the small amount of carbon dioxide present. The exhaust airstream passes through a recombination catalyst to remove the small amount of hydrogen generated by the anode-corrosion reaction. (This process is necessary because an accumulation of hydrogen would be hazardous.)

The input and exhaust airstreams also pass through a moisture-enthalpy exchanger. This unit transfers some of the moisture and heat contained in the exhaust air to the incoming airstream. It thereby reduces the battery's evaporative water losses and helps to maintain the operating temperature.

The temperature of the battery is controlled by a combination of insulation and air cooling. The aluminum-air battery operates best from 60 to 80°C. To stay in this temperature range, the battery must either be insulated or reject heat,

depending on ambient conditions, the heat loss through evaporative cooling in the air stream, and convective heat transfer from the battery surfaces. We therefore insulated most of its components but put cooling fins on the electrolyte-circulation tubes that are part of each cell.

The aluminum-air battery also requires a small auxiliary battery for starting and stopping and a system controller to regulate its operation. This auxiliary battery supplies power as needed for the various pumps and fans. The system controller drains the electrolyte into the crystallizer after the main battery is turned off to avoid anode corrosion and to prevent aluminate from precipitating in places where it might clog narrow passages and interfere with electrolyte flow. When the main battery is started, the controller refills the battery and connecting lines.

Modeling Vehicle Performance, Cost, and Energy Consumption

The effect of battery performance and design parameters on vehicle

Fig. 5

Flow diagram showing subsystems required to operate an aluminum-air battery. Subunits include hardware for storing water and reaction products, air-stream pretreatment and post-treatment, heat rejection, electrolyte circulation, and general system control.

performance, cost, and energy consumption has been determined at several stages during the evaluation of the aluminum-air-battery concept.⁸⁻¹⁰ Our most recent effort to make such determinations drew upon data from an LLNL engineering design and analysis of a parallel-plate battery,⁸ similar to that shown in Fig. 6.

Using as our baseline a vehicle similar to a General Motors X-body design with a four-cylinder ICE, we determined the mass and relative manufacturing and operating costs for

corresponding electric vehicles (using refuelable aluminum-air batteries) of the same range (400 km on 80% of fuel capacity). We also made the acceleration characteristics of these electric vehicles comparable to those of today's economy diesel and gasoline automobiles by choosing appropriate values of the peak-power-to-mass ratio (PMR).

Figure 7 compares curb mass, manufacturing cost, and operating cost of the baseline ICE vehicle with those of electric vehicles having PMRs of 30,

Fig. 6

Conceptual layout of the major components of a 40-kW, 70-kW·h aluminum-air battery. The cell stack consists of 68 series-connected cells in two 34-cell modules. The air plenum and carbon dioxide scrubber are located between the cell modules.

Fig. 7

Comparison of the curb masses, manufacturing costs, and operating costs of a conventional internal combustion engine vehicle (taken as the baseline) and aluminum-air-powered vehicles of equivalent range and equivalent or reduced power. Range of all four examples, defined as distance covered on 80% of fuel capacity (gasoline for ICE and water for aluminum-air), is 400 km. (Aluminum-air batteries contain enough aluminum for a 1600-km range, but the vehicle cannot conveniently carry that much water.) Results are based on the near-term aluminum-air-battery model.

40, and 50 W/kg. Curb mass of the electric vehicles falls within $\pm 25\%$ of the baseline ICE vehicle, indicating that aluminum-air propulsion can power vehicles with masses similar to those of today's gasoline-fueled vehicles.

The manufacturing cost of electric vehicles exceeds that of the baseline automobile by 25 to 100%. The manufacturing cost of the aluminum-air batteries is forecast to be \$19 to \$25/kW_{peak}, while that of gasoline engines is about \$5/kW_{peak}.

The total operating cost of the aluminum-air electric vehicles ranges from 40 to 90% greater than that of the baseline vehicle today. Most of this increase is due to higher fuel cost and the periodic need to replace air-cathode modules.

Estimates of cost are difficult and perhaps premature in view of the unknowns in alloy performance and cost. However, based on the fabrication cost detailed in Table 1 and a fuel efficiency of 30 to 40 vehicle tonne·km/kg of aluminum (probable to optimistic goals for vehicle efficiency), the fuel cost is about $5 \pm 1\text{¢/km}$.¹¹

A cost of 5¢/t_{Al} (based on a stable price of aluminum of about \$1.67/kg) may seem high, especially when gasoline selling for \$1.20 per gallon indicates 3¢/km in a comparable intermediate-sized vehicle. The current prices of both gasoline and aluminum (now about \$1.00/kg) are anomalously low—chiefly because of low demand and oversupply in a recession economy, the success of secondary (recycled) aluminum, and the relative quiescence of the oil-producing regions of the world. A price restoration is expected for both.

The total energy consumption of an aluminum-air battery (assuming current smelter technology) would be roughly comparable to that of using synthetic liquid fuels in economy automobiles. The introduction of vehicles powered by aluminum-air batteries would have little effect on the nation's consumption of electricity, since only a small fraction of the total would be used by vehicles. For instance, for each million vehicles introduced, the annual demand for electricity would increase by less than 0.3% of today's level. Furthermore, major improvements in smelting technology can be expected in the time before any alternative vehicle could develop into a sizeable fleet.

These studies tend to confirm our initial estimation that aluminum-air batteries might compete with synthetic liquid fuels in a petroleum-scarce economy. They cannot, however, compete with conventional sources of

Table 1 Estimates bearing on the cost of aluminum fuel plates, in dollars per kilogram of aluminum.¹¹

Cost factor	Incremental cost ^a \$/kg
Base price ^b	1.67
Fabrication ^c	0.154
Alloying agents ^d	0.053
Premium purity ^e	0.077
Retail markups ^f	0.078
Installation surcharge ^g	0.022
Credit for hydargillite ^h	- 0.306
Total	1.74

^a1981 U.S. dollars, before tax; the 1983 price is below \$1.00/kg. As with gasoline, the current price of aluminum is anomalously low because of oversupply and low demand in a recession economy. Both gasoline and aluminum prices are expected to return to their earlier levels.

^bU.S. industry published price for ingot delivered to any point in the continental U.S., 1981.

^cRectangular plates sheared from continuously cast sheet.

^d0.04 wt% gallium, 1.0 wt% magnesium, and 0.04 wt% manganese.

^eLess than 0.04 wt% iron.

^fBased on a profit per vehicle equal to that for a conventionally powered automobile.

^g\$10/h, 0.25 h every 3000 km.

^hValue at the smelter, minus profit, collection, transport, and processing.

liquid fuels. A clear advantage of using aluminum might lie in the attendant flexibility in the selection of primary fuels and the ability to adapt to an uncertain future. Whatever primary energy source is available can be used in aluminum extraction, and the electric utility and smelter may be located virtually anywhere. Finally, several aluminum companies are now developing carbothermic (direct) reduction processes, and other advanced processes that may greatly reduce the amount of electricity needed to extract aluminum.

Conclusion

In the past four years, this program has essentially established the technical feasibility of using aluminum to power a general-purpose vehicle. To fully establish the practicality of such a power source requires the engineering of a full-scale prototype—a project that, though quite difficult, should now be straightforward. Ultimate economic attractiveness in the post-petroleum world depends on a number of factors that cannot be accurately assessed today. Some of them are:

- The degree to which the cost and efficiency of the aluminum anode plate can be improved.
- The rate at which conventional sources of oil are depleted.
- The technical and economic future of synthetic fuels.
- The impact of carbonaceous fuels on the environment and atmosphere.
- The extent to which the long-range energy problem engenders advances or innovation in aluminum-production technology.

This battery technology has attracted a number of private companies, and parallel programs now exist in industry. This year, the Laboratory will choose a prime subcontractor who will gradually take over the job of developing the battery toward the ultimate goal of a commercial electric vehicle. □

Key Words: air cathode; aluminum-air battery; electric vehicle.

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Offense and Defense

Dr. Edward Teller, Associate Director Emeritus, delivered the following remarks at the Nuclear Design Colloquium held at the Laboratory on January 13, 1983. This is an unclassified version of Dr. Teller's speech, which is particularly timely considering the recently heightened national interest in the subject he addresses.

The question of whether nuclear weapons need remain exclusively weapons of destruction or whether and to what extent they can be used for defense has not been discussed very widely. It has been generally assumed that nuclear weapons have no other role than that of mass destruction. Of course, nuclear explosives could have important nonmilitary uses as studied in the Plowshare Program, but I don't want to talk about that today.

In part, the idea that nuclear weapons are of necessity purely destructive goes back to the first and only use of nuclear weapons, in Japan. Logically, this historical fact need not have a strong influence, but in reality it does.

There is an exceedingly simple formulation of the idea that nuclear weapons are exclusively destructive and that there is no defense against them. It is so simple that it seems to settle the issue in a definitive manner that makes further discussion unnecessary or, indeed, even irrelevant. And, of course, it would be wrong not to recognize this situation and answer it. The simplistic formulation is: nuclear weapons are so immensely destructive that, if one puts up a defense which will eliminate the greater part of an attack (even 99%), the percentage that comes through is still "unacceptable." Therefore, the problems of a defense become so difficult as to make an attempt not worthwhile. I think most of us have either heard this argument or thought about it ourselves.

This line of reasoning, though incorrect in conclusion, has in it a feature that is correct. The truth is that nuclear weapons for purposes of attack are very cost effective, and, therefore, one might expect to be able to build many times (perhaps 100 times) more weapons than the estimated minimum required. This has traditionally been done with conventional military projectiles such as arrows, bullets, and artillery shells. But having formulated the issue in this manner, the fallacy of the original argument becomes obvious, and it is a quantitative matter. The total cost of preparing a military deterrent

based on nuclear weapons is dominated, not by the cost of this Laboratory or the even much bigger cost of manufacturing the nuclear weapons, but by the cost of the delivery systems. It is the cost of the "bows, rifles, and guns" that determine that a factor of 100 increase is not feasible. The issue of the role of defense should not be judged in absolute terms but in quantitative terms. In particular, in terms of what gives the maximum security for the resources available.

A corollary to the argument that nuclear weapons are highly lethal and destructive beyond the intended effect is that any defense must be conventional. Even if a defense could be nuclear, the argument goes that the public would not accept it. Therefore, we must stay with conventional defense and, therefore, defense which already has to be "perfect" is made doubly impossible because one should not use nuclear explosives in defense—only in offense. This type of argument completely distorts the issue, and in the public mind it is so distorted.

Now let me talk for a moment about generalities concerning attack and defense—not only nuclear, but any type of attack and defense. There are qualitative differences between the two. Attack has advantages; defense has advantages. The advantages in attack are that the attacker has the initiative. He can plan in a more assured manner than the defender because he knows what is going to happen, at least at the start. The attacker has a particularly great advantage if there is novelty in a weapon. In this case his opponent cannot imagine how the attack will work out, and planning the defense becomes particularly difficult. This situation has played an important role in the case of nuclear weapons.

The defense has an advantage in that the defender can stay at home; his legs don't get tired, his horses don't get tired; and, to speak in more modern terms, his budget does not get tired. The defense fires his rockets over a shorter distance, and they may carry a payload with less explosive power and

with less weight. In this respect defense is cheaper. On the other hand, the defender may not know what to defend against. He has to be prepared for a variety of things.

But as one thinks more about the subject, what has to be defended against becomes clearer. And the variety of possibilities that have to be defended against become less formidable if you are ingenious. Therefore, the difficult part in developing a worthwhile defense is to be sufficiently ingenious. The objective of the attack is to have sufficient power, sufficient numbers, and sufficient money. Attack is a matter of using sufficient brute force, nuclear or nonnuclear. An effective defense is more a question of invention, intelligence, and foresight.

It is easy to understand how, in the modern age, circumstances work to create public opinion that is based on a belief in the efficacy of attack. Since the public, at least in the democracies, knows that war is a brutal business (which it is), it is believed that it has to be carried out by brute force, but despite this persuasion it need not be so. Furthermore, for most of us it is painful to think seriously about these matters, and so we prefer not to do it. Therefore, in public discussions the possibilities of defense don't come to the fore. Yet this is the issue we have to get discussions going on, and we must make sure they are both clear and public.

Before entering the main part of what I wanted to say, I would like to talk a little about attack *versus* defense in the light of the experiences of the First and Second World Wars. It's quite remarkable that in these two instances dominance by attack or defense came out in opposite ways.

The remarkable thing about the First World War was that it was the first instance of massive application of technology to warfare. And it was introduced in both a massive and an accelerating form. At the beginning of World War I there was one exceedingly important new technique: the machine gun. Machine guns were actually

available for decades before the First World War, but armies were not sure how to use them and were reluctant to introduce them widely.

It is interesting that in spite of the introduction of a technological development that had all the characteristics of an aggressive weapon, the machine gun became a weapon that finally aided defense the most. Defense against the machine gun was obvious and was immediately found: it was the trench. Indeed, the machine gun is highly lethal, but it kills only men in the open, and the men who need to be in the open are the attackers. Therefore, the machine gun lent itself naturally to the defense.

Another intrinsically aggressive technological development, which was also present before the start of World War I, was the high explosive. But the trenches stood up against high explosives, not without costs, but multiple trenches were well nigh impregnable. Only once, in 1915 on the German/Russian front, did high explosives produce a major breakthrough, and the Russians were defeated. But this was never again repeated throughout the whole war, and it became a defensive war, a war of attrition, and from this it became doctrine that defense was the thing that really counted.

Between the two World Wars the German general staff, which was not permitted by treaty to develop weapons in the usual way, was forced into ingenuity, and being technically minded, they put together a really aggressive combination. In some ways the nuclear explosive was, in effect, only the capstone to this whole new way of thinking about technologically based attack. The real success story of the Second World War was the development of the aggressive mentality. This success was due, at least in part, to the fact that people were not prepared for the greatly increased capacity for attack, and, therefore, the only countermeasure that seemed appropriate at that time was counterattack.

And so today we "know," as an absolute fact, that attack is better than

defense—not morally superior, not less terrible, but better for winning a war. This present judgment may be just as faulty as the statement after the First World War that defense was the way to win.

Now I would like to come to my main topic, and that is defensive nuclear weapons. The clearest defensive use of nuclear weapons, in my mind, is the possible use of nuclear explosives to defeat the typical aggressive weapon systems developed in the Second World War but still used in the wars fought at this time: the tank plus the airplane. The wars in the Middle East between the Arabs and the Israelis were short-duration, attacking wars with both sides using improved versions of World War II aggressive weapons. The more expert side, as opposed to the more numerous side, has won in each case, but outside of some developments in electronics the weapons have remained qualitatively the same as they were in World War II.

The extreme importance of expertise, as opposed to masses or even amounts of expenditure, is another characteristic feature of technological warfare, whether aggressive or defensive. But experience, as it is now, still supports the idea that to attack is the most effective course.

What is the alternative? The alternative—I don't like the traditional name, but that's what they are called—is the neutron bomb. These small nuclear explosives, in which neutrons and other prompt radiation play an important role while shock, heat, fallout become unimportant, could reverse the advantage presently being held by the attacker. The effect of the radiation is localized, and I am particularly interested in the smallest nuclear explosives.

If civilians are not at the actual point of fighting (in which case they will fare badly no matter how the fighting is carried out), then this small area of lethality means that it is, in general, not directed against the civilian population, and the collateral effects, in general, are small.

Of course, this new dimension could negate the advantage of the large

masses of Soviet tanks and airplanes and might even make them useless. And because of this there has been massive Soviet propaganda to counteract the neutron bomb. It was called a "capitalistic weapon" which killed humans while preserving property. One may laugh about such an argument, but for a lot of the people this absurdly comical statement is an obvious truth. I don't know of any propaganda campaign which has been as successful as the propaganda campaign against the neutron bomb. Ask your friends who know little or nothing about what we are doing whether neutron bombs will be put on intercontinental missiles. We all know how absurd such an idea is, but I guess that if you ask your wives, your children, your friends, half or more will be of the opinion that this terrible new weapon will be put on ICBMs.

I think that tactical nuclear explosives is one example where technological developments could bring about a new situation in which defense prevails. We have good, and could develop better, guidance and delivery systems for these warheads. In addition, these small nuclear weapons could be produced fairly cheaply; they are not useful for acts of aggression, and they are very useful for defense.

Perhaps the main obstruction to a serious effort at implementation of a defensive tactical system based on enhanced-radiation warheads is the widely held view that any use of a nuclear weapon will inevitably lead to escalation and eventually an all-out nuclear war. This perception suffers from the same illogic as the absolute *versus* quantitative argument I described earlier. If one is naive enough to expect an absolute guarantee that the implementation of a system for the defensive use of tactical nuclear weapons will not be involved in any way with a major nuclear war, then one is bound to be opposed to their development. But if one is realistic enough to recognize that a policy based on *defense* of territory belonging to the U.S. or our allies is a very effective way to deter aggression, both in cost and in

military terms, then this approach becomes very sensible, particularly if it is coupled with the concomitant principle of using the tactical nuclear weapons only *on* the territory being attacked.

A second category in which there are prospects for defense to become dominant is the ABM. Radar can locate incoming missiles rather well these days, and you can destroy them conventionally by putting a lot of "darts" in their path or by one or another means. This much is generally agreed to by most people whether they are for or against missile defense. Major disagreements develop when the issue of penetration aids, saturation of the defense, and effectiveness of the defense are discussed.

It is argued that the use of decoys, electronic countermeasures to the radar's effectiveness, and the harsh environment above the target areas will negate defense or, at least, allow too many warheads to get through.

The measure against the decoys is this: it does not really matter whether the incoming reentry vehicle carries a nuclear warhead or not. It does matter whether it is heavy or light. If it is heavy, then it was expensive to deliver, and there cannot be very many heavy incoming missiles. If an incoming RV is heavy then we ought to suspect it to have a nuclear explosive, and we should shoot it down. And the important point is that it can be made cost effective to shoot it down. The lighter RVs will be filtered out by the atmosphere.

There is, however, another problem but not a problem which has no solution. The trouble is that if you attack RVs with conventional means, they can be salvage fused; that is, when the first projectile strikes the incoming missile it explodes with full force, and so you don't dare attack it too low because of damage on the ground. And even if we can hit it while it is high enough above the earth to avoid damage on the ground, we are still not home free because, though there may not be any damage on the ground, there will be a lot of noise that disturbs

radar. So a second wave may reach a lower altitude before it is attacked and salvage fused, and a third wave will ladder down and finally hit. Such a defense has made an attack three times as expensive, but that is not enough. I would like to make the attack ten times—and more—as expensive.

If you use a nuclear explosive for defense, then you may melt the nuclear warhead, and you may do other things that make the salvage fusing much more difficult. In this case the laddering down that I just described becomes very tricky to accomplish. One place where an ABM defense may be applied with good effect is the Dense Pack deployment of the MX. Thirty billion dollars is being proposed as the cost of the standard MX, and this, I believe, is too much if the MX site can be destroyed with considerably smaller expenditure.

But for an additional \$8 billion, an attack on the MX field could be made exceedingly difficult and, more important, the success of an attack on the field very uncertain. I think this the time, and I mean the next few months, when we might get started seriously on a missile defense of Dense Pack. Once this is developed, we might then begin to think about how to defend New York City, or even Washington, if anyone wanted to! (Laughter)

There are lots more things that can be done about ABM defense. I would like to point out, particularly, one specific thing. Radar is not the only way to detect incoming missiles. Passive or active infrared may also be used. Passive is observing the heat from the incoming missiles; active is when you have localized the RV in first approximation by radar and then look at them with infrared lasers. With this approach, one can see them in really great detail. This makes discrimination a lot easier. If you put these infrared lasers in airplanes that can fly above the clouds, and the lasers are now available in very light weights, one might develop an all-weather capability.

The ABM, to my mind, begins to look very good, except that it suffers from

the problem that we cannot deploy it except in Grand Forks. But that's all right because I propose that whatever place we deploy Dense Pack, we call it Grand Forks! (Laughter) Seriously, I believe that ABM systems are worth pursuing with real intent at this time.

None of this is either new or classified. What is interesting, even if it is known to the Soviets, is classified, and we cannot talk about it openly. One of our prime objectives must be to find ways of convincing the people in Washington who are responsible for a realistic classification policy that they should listen to the President and not classify things where we have excellent reason to believe that the Soviets know all about it.

The possibilities and, probably, many of the details of the x-ray laser are known to the Soviets. A little more than four years ago this work was not classified, and everybody published their ideas and accomplishments. At that time the Soviets were obviously ahead of us. Then they just shut up. The same Soviet scientists are still around, but they don't publish about x-ray lasers. They don't publish about anything. Why? An obvious answer is that they noticed something which we noticed much later and which we are still not pursuing at sufficient speed.

How can these x-ray lasers be used? Well, one of the very important prospects, as most of you probably know, is the ambitious but thoroughly worthwhile goal of developing a capability of attacking and destroying the rocket boosters. These are big targets, not as hard as the reentry vehicles and very difficult to decoy. But to do this we have to know about the launch of the boosters, and, therefore, we must keep our observation posts in

operation. The prevention of the destruction of our observation posts (how to assure that all our eyes in the sky are not put out) is one of the big remaining problems, but this is not a new or insurmountable problem in the history of warfare.

Even with the possibilities that are developing, one of our acknowledged experts, Hans Bethe, who has consulted in Los Alamos and Livermore all along, writes in answer to a letter by me to *Science*, "defense against nuclear weapons is wishful thinking at best."

Despite this skepticism by some people who should be better informed and should try to remain open-minded, our work is progressing. I don't begin to believe that I have given you a complete rundown. In fact, why not use a laser in space? Well, one might. Such a scheme appears reasonable against high-flying airplanes. But, if such a system is predeployed by assembly in space, it may be shot down at the critical time. And if a conventional laser system has to be carried up by rocket, it may prove to be too heavy—although this is not completely excluded at the present time. A ground-based laser combined with mirrors in space appears much more practical.

My message today is not that defense will necessarily win. But I am telling you that a defense using nuclear explosives is on a level with nuclear attack, and anybody who claims at this stage that one or the other will necessarily give the greater advantage does not know what he is talking about. At least no one on this side of the Atlantic knows the answer. The Soviets may have thought much more about it, and they may know. And this should be our real worry. ☐

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DEFENSE PROGRAMS

Inertial Fusion

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International Security Affairs

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Diamonds: Powerful Tools for High-Pressure Physics (February 1983)
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