MASTER

MECHANICAL ENGINEERING DEPARTMENT QUARTERLY REVIEW July through September 1978

Scientific Editor: R. G. Stone
General Editor: R. A. Condouris

September 30, 1978

Work performed under the auspices of the U.S. Department of
Energy by the UCLLL under contract number W-7405-ENG-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."

NOTICE

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$; Microfiche \$3.00

Page Range	Domestic Price	Page Range	Domestic Price
001-025	\$ 4.00	326-350	\$12.00
026-050	4.50	351-375	12.50
051-075	5.25	376-400	13.00
076-100	6.00	401-425	13.25
101-125	6.50	426-450	14.00
126-150	7.25	451-475	14.50
151-175	8.00	476-500	15.00
176-200	9.00	501-525	15.25
201-225	9.25	526-550	15.50
226-250	9.50	551-575	16.25
251-275	10.75	576-600	16.50
276-300	11.00	601-up	¹
301-325	11.75		

¹Add \$2.50 for each additional 100 page increment from 601 pages up.

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California/94550

UCRL-50016-78-3

**MECHANICAL ENGINEERING DEPARTMENT
QUARTERLY REVIEW
July through September 1978**

**Scientific Editor: R. G Stone
General Editor: R. A. Condouris**

MS. date: September 30, 1978

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MGW

CONTENTS

Two-Transducer Test Bed Being Developed for Ultrasonic Imaging (*B. J. McKinley, Materials Engineering Division*) 1

Current LLL programs require improved methods for quantitative, nondestructive evaluation of bond strength, cracks, and joining. These needs motivated the LLL ultrasonic imaging project to find ways for increasing resolution and producing accurate graphic ultrasonic images. Subprojects directed at achieving these goals are 1) mathematic modeling of elastic-wave scattering for realistic defects, 2) developing signal analysis techniques to allow thorough quantitative ultrasonic field measurements, and 3) design and fabrication of a high precision, versatile, computer controlled two-transducer ultrasonic test bed with on-line computerized data acquisition, analysis, and image display. The two-transducer ultrasonic test bed that we are developing is a central feature of the project.

Warhead In-Service Status Estimator (WISE) Measures and Records Stockpile Environments (*H. K. McCue, Nuclear Explosives Engineering Division*) 9

Nuclear weapons age while in the stockpile. By careful selection of materials and by consideration of materials compatibility, the chemical aging can be slowed but not totally halted. In the past, potential problems in the areas of detonator corrosion, high-explosive degradation (sensitivity, cracks, outgassing), and materials oxidation have occurred. Because nuclear weapons do chemically age and the median age of the stockpile is increasing, it becomes imperative to estimate accurately the future functionality and safety of nuclear weapons. More precise estimates than currently available require additional weapons information. One element of this additional information is environmental stockpile data.

Water Quality Study Important in Developing the Imperial Valley as a Geothermal Energy Resource (*K. D. Pimentel, Research Engineering Division*) 14

The determination of a comprehensive data base of baseline water quality conditions before geothermal development begins is an important step in water quality management. Using these data, developers, regulators, and environmentalists can assess the impacts that geothermal development is likely to have on the valley's water resources in the future, as well as detect any changes that may occur by making similar measurements in future monitoring programs.

Mirror Fusion-Fission Hybrids Offer Versatile Energy Potentials (*J. D. Lee, Magnetic Fusion Engineering Division*) 20

We have been studying fusion-fission hybrids based on magnetic mirror plasma confinement since the early 70's. Here, we describe the fusion-fission concept and outline LLL's fusion-fission hybrid program. One hybrid reactor can supply makeup fissile fuel for as many as 10 fission burner reactors of equal thermal rating, and the capital cost of such systems is only about 25% above that of thermal fission reactors.

Impact Test of B77 Measures Dynamic Buckling of Titanium Afterbody (*W. R. Bish, Weapons Engineering Division*) 29

We conducted a tail impact test of a mass mock of the B77, with a mock titanium afterbody on November 15, 1977 at Site 300 drop tower facilities. The specified impact velocity of 9.14 m/s was attained, and the impact was flat within 1 mm. The test successfully measured the dynamic buckling characteristics of the titanium afterbody. Analyses of the test data show that the afterbody buckling load is 19% lower than the predicted value based on a NSAP-2D finite-element, computer code calculation. The dynamic buckling load-deflection curve of the afterbody, obtained from the test, will be used as input into the SHOCK computer code for calculating the peak tail impact acceleration loads in the B77 nuclear package.

Technical Notes 34

Publication Abstracts 37

TWO-TRANSDUCER TEST BED BEING DEVELOPED FOR ULTRASONIC IMAGING

The ultrasonic imaging project in progress at LLL is to increase resolution and produce accurate graphic ultrasonic images. The word "image" is used in a broad sense to include a variety of methods for displaying quantitative, nondestructive test results of materials. A central feature of the project is the two-transducer ultrasonic test bed (Fig. 1).

Our motivation comes from the need to satisfy an endless variety of LLL ultrasonic inspection requirements. The overall project goal is to make pertinent quantitative material evaluations with the highest attainable accuracy. Our requirements generally fall into four categories: 1) bond strength evaluation, 2) accurate surface crack depth measurement, 3) definition of the size, shape and orientation of material defects such as cracks, voids, and inclusions, and 4) the inspection of one of the above three categories in some complex configuration.

The present state-of-the-art in ultrasonics is limited in its ability to produce quantitative measurements. To minimize these limitations, we have concentrated our efforts on improving our theoretical understanding and developing better test hardware. The theoretical research involves mathematical modeling of the scattered elastic fields from realistic defects and perfecting signal analysis techniques necessary for quantitative field measurements. The development effort involves upgrading existing ultrasonic test beds in terms of versatility, accuracy,

online data analysis, and graphic display. The concepts for the new two-transducer ultrasonic test bed now under development have evolved out of practical experiences of the past 15 years. These experiments include ultra-precision machine tool design, ultrasonic instrument design, computer control of manipulators and data acquisition, and study of a wide range of theoretical approaches to the imaging problem. The versatility and precision of this test bed are absolutely necessary to realize the full potential of ultrasonics.

LLL Program Requirements

There is a wide variety of ultrasonic tests which we are asked to do. They differ primarily in the geometry of the objects to be inspected. In our Laboratory, as in many others, the trend towards more efficient designs has made quantitative non-destructive testing extremely important. More complex designs, high strength requirements, composite materials, and a number of new joining techniques have made dramatic changes in ultrasonics, particularly with regard to the required resolution. In general, the test requirements can be divided into four categories, which are discussed below.

Fig. 1. Ultrasonic imaging program for increasing resolution and producing accurate graphic ultrasonic images.

Bond-Strength Evaluation Problems

In bond-strength evaluation, our task is to image the size and distribution of "island of unbond" and to correlate the results with reduced bond strength. There are three types of evaluations of immediate interest. The first and simplest geometry is the plain bonded interface. Examples are diffusion bonding and plating where the bond interface position is well defined. The second, and more complicated, is the multiple plain bond interface. An example is the bonding of two dissimilar materials with a thin plating of a third material between them. The third category, which includes a braze, is referred to as a "graded interface." These interfaces are more complicated because we lack knowledge of exact location of unbond defects within the bond zone, the variation of material constituents after solidification, and the uncertainty of the reflectivity of a normal braze.

Depth Measurements of Surface Crack

Cracks that terminate at a free surface are of great concern. Our task is to describe the crack accurately. Fracture mechanics concepts can then be used to calculate the serviceability of a structure given the dimensions of the crack. An example is the "crack" that is the result of incomplete penetration of a butt weld. Fortunately, the position and orientation of such a crack is known. All we need to do is measure its depth. The complications involve variations in material properties in the weld zone and adequate resolution when the crack critical dimension is on the order of a wavelength.

Material Defect Evaluation

Quantitative measurement of the size, shape, and orientation of material defects such as cracks, voids, and inclusions is an extremely broad category. It is an area where significant advancements have recently been made, particularly in mathematical modeling of the scattering of idealized defects such as ellipsoidal voids and penny-shaped cracks. We intend to put a sizable effort into both the theory and experimental verification of the mathematical models predicted by the theory.

Inspection of Complex Configurations

Our designers are extremely clever at producing objects that are almost impossible to inspect. A great deal of our effort involves fixturing to handle complex configurations or items that are one of a kind. The greatest difficulty occurs when it is necessary to manipulate two transducers independently to perform the inspection. A simple example is a small tube

brazed into a cylinder with the tube axis not normal to the cylinder wall.

Limitations of Ultrasonics

The limitations of ultrasonics are easily stated. We need to increase resolution and produce intuitive images, or displays. The simplest way to increase resolution is to increase frequency as is done with an acoustic microscope. There are problems in inspecting industrial products that limit the frequency we can use, but in general our trend will be toward higher frequency. We need to improve the precision of our systems in an overall sense. We must design mechanical and electronic systems with a primary objective of accuracy and "built in" methods of maintaining and checking the accuracy over the life of the system. In other words, a fundamental limitation is the lack of imaging systems that can be calibrated.

There are two theoretical limitations that we are working on. First, we do not know what the fields "look like" that are being scattered by the various material anomalies we seek to evaluate. The mathematical models that presently exist only describe the simplest geometries and these rarely appear in practice. Second, signal analysis techniques are inadequate. Improvements in range resolution and spectral analysis are necessary to perform the complex correlation between ultrasonic data and physical requirements of the test object.

Solution Action

Looking at the requirements stated previously, we have recognized some fundamental limitations in our system. Our approach to correct these limitations is two-phased. First, research aimed at mathematical modeling of the scattering process and development of improved signal analysis methods are in progress. Second, we have a continuous development project intended to upgrade existing test bed hardware, control technique, and data acquisition and analysis methods.

We currently have a two-man effort in the area of theoretical work. Specifically, we are interested in solutions on approaches that can be applied to practical problems. We have reviewed the literature on solutions to elastic wave equations. In general we are interested in the approximate theories. Two examples are the diffracted ray theory and the series of integral equation solutions that started with the Born approximation and have evolved to the extended quasistatic approximation.

We are perfecting the signal analysis techniques that we use for time and frequency domain analysis. Our major effort at this point is improvement in range resolution. Recent experiments have shown (Fig. 2) that we have the capability of resolving two pulses that are separated in time by 35 ns. Estimates of the relative amplitudes were also calculated.

Development

A five-man development effort is directed toward design and fabrication of the two-transducer ultrasonic test bed. The features of this test bed (Fig. 3) represent the highest precision, versatility, and reliability. The mechanical motions are completely computer controlled. Data acquisition, signal processing, graphic displays, and ultrasonic feedback control are all computerized. The base of the test bed is a 5-m-square granite block 1 m thick. Both a horizontal and vertical spindle are included for rotating symmetric test objects. The sturdy overhead ways provide rectilinear motion of both transducers simultaneously in a controlled scan mode or for positioning the central cylindrical section relative to the test object. The central section provides two cylindrical motions (Figs. 4 and 6) that allow the two transducers to be positioned independently to any point within a 0.40-m-diam cylinder 0.30 m high. The accuracy goal is to position the transducer at a point in the space of the cylinder within a sphere of uncertainty 125 μ m in diameter with reproducibility of position within 10 μ m. There are two orthogonal angular motions that allow the transducer to "look at," or be directed at, any point in the cylinder completely independent of the position motions. This is a new concept for positioning the transducers relative to the test object. (See Fig. 5.)

The principal of the concept is to maintain a fixed point in space at which the transducer is "looking" while changes in transducer angle relative to that point are made. The simplifying features that make this possible are: First, the motions used to position the transducers in space are completely independent of the motions used to control the angular direction of the transducer, and second, the angular manipulators rotate about a fixed point in space. This greatly improves accuracy and simplifies the motions necessary to "map the field." I consider mapping the field at the water-to-part interface the most common mode of operation. For example, suppose we were to inspect a weld in a sphere. We would mount the sphere on the horizontal spindle with the weld in the vertical plane. The transmitting transducer would be positioned and the angle set for a refracted shear wave incident on the weld zone. The scattered field at the outside surface of the sphere would be recorded

by manipulating the position of the receiving transducer over the necessary surface area while constantly changing its angular directions to be normal to the wave fronts of the scattered field. There are 14 precision axes of motion on this test bed. Figures 6a and 6b show the six linear slideway axes and the eight rotating axes. The computer control system (Fig. 7) will provide various control modes, including a "learning" mode that allows the operator to establish a routine for moving the transducer over an object. This is especially important when the test object is not a simple shape, or accurate dimensions are not available.

Ultrasonic instrumentation is constantly being upgraded as new electronic innovations become available. The latest addition to our system is a high-speed transient waveform digitizer. It has a 500-MHz sampling rate with 6-bit accuracy for a single recording cycle of 1024 data points. Improved resolution is easily attained by averaging.

The ultrasonic system was designed with calibration in mind. For example, it has a built in 25-MHz reference signal used to calibrate amplifiers and the peak rf amplitude to dc conversion section. We are looking for better methods of making this conversion that will increase the linear dynamic range. We periodically calibrate or at least tabulate the following system parameters:

- Pulser—peak voltage, width, overshoot, repetition rate.
- Receiver—gain bandwidth, linearity, noise figure, overload recovery time for both large and small overloads
- Gates—width, position accuracy (jitter).
- Peak Sampling—linearity, dynamic range, effective bandwidth.

Unique Test Bed Capabilities

The most fundamental motive for building the two-transducer ultrasonic test bed is the growing necessity in routine inspection for two transducers—a transmitter and a receiver—which are accurately and independently manipulated.

The mathematical models we are now generating are new approximate solutions for which no complete solutions exist. The mechanical versatility and accuracy of the two-transducer ultrasonic test bed is absolutely necessary to experimentally verify the approximate solutions.

A very significant use of this test bed will be in feasibility studies where we identify, quantitatively, all the parameters necessary to design a production-line inspection fixture. The largest portion of our

Fig. 2. Range resolution experiments show that we can resolve two pulses that are separated in time by 35 ns.

1. Precision cylindrical position manipulator
2. Transducer angulation manipulator
3. Tailstock for horizontal spindle
4. Water bath tank
5. Vertical spindle base
6. Control system central processing unit
7. Teletype-display console
8. Manual control console
9. Ultrasonic instrumentation

Fig. 3. Two-transducer ultrasonic test bed.

effort has been in designing fixturing. A problem we constantly face is designing a test bed to do a feasibility study that later is used in the production test. There are several problems with this approach. More versatility must be designed into the system to do the feasibility study than is necessary to do the actual test. There is a problem with the time lapse necessary to build anything. The cost of adequate systems is prohibitive for a small program. When the job is complete, the system goes to the production line, and we are left with nothing but a technical report from which to start on the next task.

Conclusions

An ultrasonic imaging project is underway at Lawrence Livermore Laboratory. We are addressing the theoretical problems of mathematical modeling of scattering by realistic-defect geometries. We are perfecting the instrumentation and analytical techniques necessary for adequate ultrasonic signal analysis. We are building the sophisticated precision two-transducer ultrasonic test bed necessary to achieve the full potential of ultrasonics as a quantitative nondestructive test.

Fig. 4. Schematic of cylindrical manipulations.

Fig. 5. Transducer angulation manipulations.

Fig. 6. Fourteen precision axes of motion: (a) six linear slideway axes and (b) eight rotating axes.

Fig. 7. Computer control system for ultrasonic imaging.

WARHEAD IN-SERVICE STATUS ESTIMATOR (WISE) MEASURES AND RECORDS STOCKPILE ENVIRONMENTS

As part of the surveillance program, we are developing an electronic data acquisition system for unattended monitoring of the stockpile environment. The WISE (warhead in-service status estimator) package is a first generation of self-contained, unattended "black boxes" designed to measure and record the stockpile environments of individual warheads. This WISE package monitors warhead surface temperature and shipping container percent relative humidity.

Figure 1 shows how the WISE package fits in the container, and fig. 2 shows the data collection sequence. During the logging period, the WISE box,

Fig. 1. WISE system in place in the shipping and handling container with a mock W-48 155mm atomic projectile.

Fig. 2. WISE package, located within the container, reads the sensors and processes these data every 20 min. Later the package is removed and the logged data are written onto the tape cassette and read directly into Octopus, LLL's timesharing computer system.

located within the warhead shipping and handling container, reads the sensors and processes these data every 20 min (typical sampling interval). At the end of the logging period, the WISE package is removed, and the recorded data are written onto a tape cassette by a Texas Instrument Silent 700 ASR terminal. An Octopus computer terminal reads the cassette into the Livermore timeshare system. (Octopus is the name given to Livermore's computer network.) Because the WISE data are in a digital format, it can be directly read into the computer system without going through tedious manual inputting. In the Octopus system, the WISE data are processed into tabular listings and plots.

WISE records temperature data in two formats: time-integrated data (TID) and time history. Figure 3 shows the time-integrated format. TID processing divides the temperature span (-54 to $+74^{\circ}\text{C}$) into 32 intervals, and determines the total time spent within each interval. Figure 4 shows the time history format. For this plot, the temperature of a thermal mass with a 35-min time constant was sampled every 20 min. The data compression algorithm selects those samples that are needed to describe the temperature curve accurately; only the points marked "X" were stored. All other sample points were reconstructed from the stored points, and are within $\pm 1^{\circ}\text{C}$ of the actual temperature. Using a relatively few number of stored points, the data compression algorithm allows the storage of the complete temperature and relative humidity time histories.

Fig. 3. Computer output of temperature in time-integrated data (TID) format. TID processing divides the temperature span of -54 to 74°C into 32 intervals and determines the total time spent in each interval.

Fig. 4. Computer output of temperature in time history format. The temperature of a thermal mass within a 35-min time constant is sampled every 20 min. The data compression algorithm selects only those samples (X) needed to describe the temperature curve accurately.

System and Data Acquisition Characteristics

Some system and data acquisition characteristics of the WISE feasibility package are summarized below:

- **Logging time**—The maximum logging capacity varies with the warhead thermal time constant and WISE sampling interval. For a thermal time constant of about 35 min and sample interval of 20 min, the WISE package has a nominal 1-year capacity.
- **Temperature data**—Temperature data are available in two formats: TID and time history. The reconstructed time history has a maximum error of $\pm 1^\circ\text{C}$ over a span of -54 to $+74^\circ\text{C}$.
- **Relative humidity data**—Percent relative humidity data are available in time history form. The reconstructed relative humidity data has a typical error of $\pm 5\%$ and a maximum error of $\pm 7\%$ over the 0 to 100% span.
- **Operating temperature**—All portions of the WISE package, except for the relative humidity sensor, operate over the -54 to $+74^\circ\text{C}$.
- **Sampling interval**—The sampling interval is hardware adjustable in 1-min increments from 2 to 255 min.
- **Weight and volume**—The circuit boards containing the electronics, sensors, and lithium batteries have a volume of $1.8 \times 10^3 \text{ cm}^3$ and a mass of 1.5 kg. For the circuit packaging shown in fig. 2 (the above components plus baseplate and cover), the total mass is 3.3 kg.

- **Database**—The WISE data are to be stored digitally and as such can easily be incorporated into existing databases without tedious manual inputting.

- **Power consumption**—The average power dissipated is about 1 mW.

- **Data reduction**—The WISE package carries all the information needed for data reduction in its nonvolatile memory. This includes sensor and time-base calibration data, weapon type and serial number, WISE serial number, WISE startup time, and sampling interval. These data and more are written onto the tape cassette along with logging information.

Computer Terminal Function

In addition to its data acquisition function, WISE also has a computer terminal function. This mode allows the user to write the stored environmental data onto a tape cassette, manually read the sensors, and write a note and current time to memory. The note command allows the user to record, with respect to the WISE time base, when significant events occur (e.g., WISE package mated to warhead).

Before WISE grants access to the terminal mode, the user must supply a five character combination; for this terminal, there are more than 7.7×10^9 possible combinations. The user is given four tries at the combo. If he fails on the fourth attempt, the WISE package inhibits the terminal mode for 24 h (assuming a 20-min sampling interval).

In addition to logging environmental data, WISE monitors how the people are using the system. While in the terminal mode, significant terminal activity, along with current time, is recorded for future reference; these activities are:

- Access granted to terminal mode.
- User-initiated "bye"-out.
- Timed "bye"-out (no terminal activity for 4.5 min).
- Tape cassette written.

WISE also monitors its own performance. When activated to process the sensor data, WISE checks for abnormal conditions; if found, this fact along with current time is recorded in nonvolatile memory. The four conditions checked are:

- Low battery voltage.
- Error in "always-on" CMOS RAM (complementary metal oxide semiconductor random access memory).
- Fatal error in double-precision arithmetic package.
- Phantom power up (microcomputer turned on by unidentifiable source).

If the battery voltage, when compared to a WISE adjusted reference, is low, then the battery voltage is also written into memory. If any of the last three faults are detected, WISE initiates corrective action.

WISE System Description

Recent advances in technology [low-power large-scale integrated (LSI) microcircuits, non-volatile memories, and lithium batteries] combined with the processing ability of a microcomputer, now make practical remote monitoring and logging of warhead environments. WISE takes advantage of these recent developments.

All power for the WISE feasibility package comes from internal lithium (Li/SO_2) batteries. For this application, lithium batteries have attractive features: long shelf life (10 y), wide temperature range (-54 to $+74^\circ\text{C}$), and high energy density $0.43 \text{ Wh}/\text{cm}^3$. Even with the incredible energy density of

lithium batteries, it was still necessary to minimize the average power drain. With conventional circuit packaging, the battery represents 20% of the volume and 35% of the weight; if hybrid packaging were used, the battery would easily be 75% of the volume and weight. Three techniques were used to minimize the average power: CMOS low-power circuits, power management, and data compression.

Figure 5 shows the functional block diagram for the WISE package. Power is always applied to the shaded boxes and power is only applied to the remaining boxes when the microcomputer is in the active state. The "always-on" portion consists of the interval timer (used to activate the microcomputer at periodic intervals) and 1K-bit CMOS RAM (e.g., used to hold TID data, uncompressed data points). The majority of the time (99.8%), the unshaded portion of the system is dormant; this power management reduces the average power drain. The Intersil IM6100 12-bit microcomputer forms the heart of the dormant portion; at the instruction set level, this microcomputer looks like the DEC PDP-8 minicomputer. For this application, 3K words of CMOS

Fig. 5. Functional block diagram of WISE package.

ROM (read only memory) program storage and 256 words of scratch pad RMA (random access memory) are used. Also included in the dormant portion is the analog sensor section and nonvolatile FAMOS (floating-gate avalanche-injected metal oxide semiconductor) memory; each of these are power managed by the microcomputer.

The analog input/output section interfaces the temperature sensor (platinum resistance thermometer) and relative humidity sensor (Brady array) to the microcomputer. The nonvolatile memory holds the compressed data points, combinations, system data, calibration data and error messages; it incorporates the Intel 2716 FAMOS chip and is organized as a 14K by 8-bit memory. When the data logging is completed, the user connects the Silent 700 with tape cassette to the WISE box; WISE writes and verifies the stored data in about 10 min. All portions of the WISE feasibility package except for the relative humidity sensor operate over the -54 to $+74^{\circ}\text{C}$ temperature range; the relative humidity temperature range is 0 to 50°C .

How A Typical Sampling Code Sequences

At a timer interval determined by hardware jumpers, the "always-on" timer awakens the microcomputer through the RESET line. After initializing itself, the microcomputer powers up the analog sensor section, reads the sensors, and then powers up the analog sensor section, reads the sensors, and then powers down the analog sections. During this sequence, the nonvolatile FAMOS memory remains unpowered.

Next, the sensor data are processed by the algorithm described later in this section. If a data point must be stored in nonvolatile memory, the microcomputer powers up the FAMOS memory, stores the data point, verifies the data point, takes corrective action if the data point does not verify, and powers down the memory. Upon completion of this cycle, the microcomputer powers itself down; this section will remain dormant until awakened again by the "always-on" timer.

For the sampling cycle just described, the microcomputer is activated for about 2.5 s. Special hardware protects the "always-on" RAM and FAMOS memories against power-up and power-down transients. Occasionally, one will connect the Silent 700 terminal to the WISE box to collect the stored data.

For sampling intervals over 10 min, the data logging and terminal sessions can simultaneously share the microcomputer without loss of data; maximum delay in reading the sensors is a few seconds.

Data Processing

WISE processes sensor data in two ways: TID (time-integrated data) and compressed time history. The TID processing requires minimal computation time (both in the WISE package and in the CDC 7600) and no nonvolatile memory. Unfortunately, the TID processing loses much of the information contained in time histories. Data compression reduces the number of sensor readings that must be stored; this, in turn, reduces the WISE volume and weight. In the feasibility package, temperature data are processed both ways, whereas percent relative humidity data are only compressed.

TID Algorithm

In TID processing, 32 intervals divide the temperature range (-54 to $+74^{\circ}\text{C}$). When the timer activates the box and the sensors are read, the TID algorithm determines which of the 32 intervals the temperature reading falls within; the count in this interval is then incremented. The count in an interval is proportional to the total time that temperature spent in the interval. The counts are converted to a "time-at-temperature" bar graph in the CDC 7600. Because the count information is frequently changing and power conservation is important, the counts are stored in the "always-on" CMOS RAM.

Data Compression Algorithm and Test

The WISE compression algorithm assumes that the temperature being monitored is associated with a thermal mass and that the "quickest" thermal input is steplike. Under these conditions, the temperature will be a smooth function when observed over several thermal time constants. Thus, polynomial functions can accurately approximate temperature in this time interval.

Figure 6 illustrates the WISE compression algorithm. The dots represent the actual temperature readings. Since the box sampling time was selected to be less than the thermal time constant, one knows that these dots are connected by a smooth temperature function; this is shown by the solid curve. The square boxes surround previously determined compressed data points; these two points are stored in the nonvolatile FAMOS memory. The triangle encloses the current temperature reading. The two dots between the current reading and the last compressed data point are held as 12-bit readings in the compression stack; the compression stack resides in the "always-on" CMOS RAM. These two data points have previously passed the compression test described below. Given the last two compressed data

Fig. 6. WISE compression algorithm. In this example, the current temperature readings in the shaded area passed the compression test.

points and current reading, one can curvefit the temperature function with a quadratic of the form

$$T(t) = a + bt + ct^2,$$

where T is temperature and t is time.

The three distinct data points uniquely determine the three coefficients a , b , and c ; these coefficients can always be computed by a noniterative procedure. Figure 6 shows the curvefit as a dashed curve. The absolute value of the maximum error between the actual data points and the approximated data points (in the time interval between current and last compressed data points) is formed. If this maximum error is below some specified threshold (shaded area in Fig. 6), the current reading passes the compression test. For the example shown, the current reading passed the compression test; that is, the actual data points all lie within the shaded region.

If the current reading passes the compression test, then it is temporarily stored in the compression stack. The next sample time, the new current reading is used to approximate the three temperature readings in the compression stack. As long as the

compression test is passed, this process is allowed to continue up to 15 samples past the last compressed data point; the 15th sample point is forced into FAMOS memory.

If the current reading failed the compression test, the sample taken just prior to the current reading would become a compressed data point; this point, in another compression test, passed, and thus adequately described the temperature curve. By this process, compressed data points are selected from the sensor readings. When these data are reconstructed on the CDC 7600, the temperature curve will have a maximum error equal to the tolerance band error plus sensor reading error. The compression algorithm used guarantees no additional roundoff error in the reconstructed data. We have demonstrated the utility of this algorithm on actual temperature and relative humidity data, with a WISE breadboard.

Conclusions

As part of the surveillance program, we are developing an electronic data acquisition system for unattended monitoring of the stockpile environment. Currently, a first generation WISE package for monitoring warhead temperature and shipping container percent relative humidity for up to 1 year has been developed. The temperature data are recorded in both time-integrated and time-history forms; the relative humidity data are recorded in time-history form. The WISE package is totally self-contained and as such requires no external connections or energy sources during data collection. The WISE package has a volume of $1.8 \times 10^3 \text{ cm}^3$ and a mass of 3.3 kg. In addition to logging environmental data, the WISE package monitors its own performance and how people use the system. All information required for data reduction, such as calibration, weapon ID, package ID, are carried in an internal nonvolatile memory.

Future work includes testing the WISE package using a mock W-48 155mm projectile in its shipping and handling container. Possible WISE enhancements are: incorporate acceleration monitoring, extend logging time up to 8 years, and incorporate a new relative humidity sensor that has a wider temperature range.

WATER QUALITY STUDY IMPORTANT IN DEVELOPING THE IMPERIAL VALLEY AS A GEOTHERMAL ENERGY RESOURCE

In 1975, the Department of Energy requested LLL to plan and implement an integrated environmental baseline and assessment study in the Imperial Valley, California in support of anticipated geothermal energy resource development. This study eventually became the Imperial Valley Environmental Project (IVEP) and included studies by LLL and subcontractors. We also coordinated with the efforts of many other organizations to achieve a comprehensive integrated project. Included in this project were several effects studies, but the primary data collection effort was oriented toward the definition of baseline conditions. From the outset, it was agreed that the baseline data collection efforts would be carried out over a 2-year period. During and following this period, we were to complete predictive assessments of future environmental changes. Most of the field programs concluded in April 1978, with integrated assessment of environmental effects continuing on into FY 1979.

The water quality study is one of seven major studies that constitute the IVEP. Objectives of the water quality study are:

- To accumulate baseline data on chemical water quality throughout Imperial Valley.
- To detect and evaluate any impact of geothermal development on water quality.
- To participate in the evaluation of alternate heat sinks for geothermal power.
- To participate in regional water resource analyses.

We are accomplishing these objectives by accumulating water quality data already available from many federal, state and local agencies, by collecting additional data specific to our needs, and by integrating these data into an overall assessment.

We established water quality sampling networks in 80 locations to monitor municipal drinking water supplies, some domestic water wells, agricultural canals and drains, the two major rivers in the valley, and the Salton Sea. Coverage was emphasized in the four major Known Geothermal Resource Areas (KGRAs) in the valley: Salton Sea, Brawley, Heber, and East Mesa (see Fig. 1). Developers are planning to construct no less than six demonstration power plants affecting the four major KGRAs in the next 5 years. Recent estimates indicate that 2000 MWe should be on-line by the early 1990s; the total energy of the valley's geothermal resources has been estimated to exceed 130 GWe-yr. Thus, it has been imper-

ative to document water quality in these areas before large-scale development occurs.

Baseline Water Quality

Baseline water samples have been collected monthly for 13 months. Analyses on these samples have included the following major constituents and trace elements:

- Na, K, Ca, Mg, Cl, SO₄, CO₃, SiO₂, TDS, SC, pH, and temperature.

- Ag, As, B, Ba, Cd, Cr, Cs, Cu, F, Fe, Hg, Li, Mn, Mo, Ni, Pb, Rb, Se, Sr, V, and Zn.

We chose these chemicals because they include constituents that were known to be abundant in many of the geothermal brines in the valley and because many of them are highly toxic. It was important to document baseline levels of these chemicals before large-scale development of the valley's geothermal resources takes place to show that high levels of certain chemicals are a naturally occurring phenomenon and not necessarily caused by geothermal development.

To demonstrate some of the baseline levels of chemicals and different types of water we encountered in the valley, we use diagrams in Fig. 2. These diagrams show relative levels of major constituents in the waters and levels of five important trace elements. The sets of diagrams in Fig. 3 (a) summarize average baseline chemistry of geothermal wells in the four major KGRAs in the valley and in an area outside the Salton Sea KGRA near Westmorland. To assess the environmental impacts of large-scale geothermal resource development on water quality, the data in these diagrams would be used to estimate "source terms" of geothermal brine contamination or pollution. Plausible releases of these fluids include accidental spills caused by well blowouts, piping failures, cooling tower sump failures, and so on. The diagrams in Fig. 3 (b) summarize average concentrations of many of the important chemicals found in geothermal brine for five types of water sampled in the valley: agricultural canal water (from which municipal water supplies in the valley also originate), agricultural drain and sump water, river water, and water from the Salton Sea. The rows of numbers at the bottoms of the diagrams in Fig. 3 (a) and (b) for each water type are for two important chemical ratios that serve as geothermal markers or "fingerprints" of geothermal water: K/Na and Cl/SO₄.

Fig. 1. Imperial Valley, California, showing Known Geothermal Resource Areas (KGRAs) where work is being done in the Imperial Valley Environmental Project (IVEP).

Fig. 2. Stiff diagram for major constituents and logarithmic diagram for trace elements. In the Stiff diagram, positively-charged ions are plotted to the left and negatively-charged ions to the right in percent reactance. The bar in the center shows total dissolved solids (TDS) plotted on a logarithmic scale. The trace element diagram is plotted in equivalents per million on a logarithmic scale. This figure defines the diagrams used in Figs. 3(a), 3(b), and 4.

The major constituents (Fig. 2) vary greatly in valley water, but are comprised mostly of Ca, Mg, Na, SO_4 , and Cl. Notice how the incoming irrigation water in the canals is relatively high in Ca and SO_4 . The irrigation water is so saline to begin with in the valley [averaging 992 mg/l total dissolved solids (TDS)] that to successfully irrigate with it, networks of porous drain tiles have been placed 2 to 4 m deep and from 15 to 30 m apart in nearly all the agricultural fields in the valley. These tiles collect excess irrigation leaching water that is used to wash accumulated salts in the soils down away from the root zones of the growing crops. This tile drainage water collects in concrete sumps at the corners of the fields. Thus, the sump water represents water that has leached through several meters of soil, dissolving out various minerals as it goes. The main features in the sump water is the elevated NaCl relative to the canal water and the lower value of SO_4 .

The two ratios K/Na and Cl/SO_4 (Fig. 3) are indicative of the differences among canal, sump, and drain water; they are also markers for geothermal water. High K relative to Na, and high Cl relative to SO_4 are directly related to how hot a geothermal water has been when it was last in equilibrium with minerals in the rocks at depth. At high temperatures, salts of K dissolve out of the rocks at a much higher rate than at normal surface temperatures. This relationship is so sensitive an indicator that prospectors for geothermal resources use an empirical function involving Na, K, and Ca to estimate the temperature of a geothermal resource from its brine

chemistry. Thus, from the two lines of numbers in Fig. 3(a) and (b), we can see that these two ratios, K/Na and Cl/SO_4 , are good markers to distinguish geothermal brines from normal surface waters in Imperial Valley.

In irrigating any given field, normal practice is to use a little more water than is needed for crop growth and for leaching; this excess "tail water" usually runs off the far end of the field and into an agricultural drain. The net effect of this practice can be seen in the Stiff diagrams for average drain water in the valley. The shape of the diagram lies between the shapes of the diagrams for canal and sump water as expected, showing that the drain water is a mixture of canal and sump water.

Trace elements are abundant in geothermal brine and much more concentrated than in surface waters. Figure 2 also defines the plots at the bottoms of Fig. 3(a) and (b) that include five of the trace elements that are elevated in the brines: B, Li, Mn, Sr, and Zn. Note the levels of these elements, particularly in the Salton Sea KGRA brines. They are orders of magnitude higher in concentration than in canal and drain water. We suspect that in future monitoring studies some of these trace elements will form a reliable fingerprint for detecting geothermal brine intrusion into surface waters. Note that the mixing of excess irrigation water (tail water) with sump water in the agricultural drains is also evident in the trace element diagrams; the levels of the five plotted trace elements for drain water lies between those for canal and sump water.

(a)

(b)

Fig. 3. (a) Average properties of geothermal brines. (b) Average properties of Imperial Valley waters. (See Fig. 2 for definitions of diagrams.)

Vail 4A Drain Case Study

A case study that illustrates our findings in Imperial Valley concerns the pollution of the Vail 4A Drain (Fig. 4). In establishing monitoring networks in the Salton Sea KGRA, high concentrations of many chemicals were encountered in an agricultural drainage sump adjacent to the Sinclair 4 geothermal well. These levels of chemicals suggested that the large amounts of crystalline salts in the evaporation

ponds surrounding the geothermal well were causing pollution. In studying the area, we found that salts were leaching from the evaporation ponds into a buried agricultural tile drainage system in the field east of the ponds. The leaching water flows through the tiles into a concrete sump (Sump 116) that is periodically pumped into Vail 4A Drain, which empties directly into Salton Sea.

The map in Fig. 4 shows the sites where water samples were collected in the vicinity of the Sinclair 4

Fig. 4. Area near the Sinclair 4 geothermal well in the Salton Sea KGRA showing sample sites used in the Vail 4A Drain case study. Diagrams of major ions and trace elements are defined in Fig. 2.

geothermal well. The flow in the canals and drains is northward toward the Salton Sea. The incoming irrigation water was sampled from Vail 4 Canal a mile upstream of the Sinclair site. Sump 120 is a typical sump that collects leaching water from a field that is unaffected by geothermal development. The Sinclair 4 well was drilled in the mid-1960s and operated from time to time to conduct material corrosion tests and to experiment with alternative reinjection methods. The way it was used was the brine was flowed from the well through the test apparatus and then into holding ponds until the ponds were full. The well was then shut off until the ponds had evaporated and new apparatus was installed for another test. This cyclic filling of the evaporation ponds resulted in thick crusts of salts that eventually leached through the unlined bottoms of the ponds into the surrounding groundwater. This brine was showing up mixed with leaching water in samples we took from Sump 116. A sampling site about a mile downstream of this area in

Vail 4A Drain is shown on the map. Sites in the Alamo River and Salton Sea are also shown for comparison.

The diagrams in Fig. 4 are Stiff diagrams for major constituents and logarithmic trace element diagrams as described earlier in Fig. 2. These diagrams show clearly what is occurring near the Sinclair 4 well. The incoming irrigation water is high in Ca, Mg, NA, HCO_3 , and SO_4 , but relatively low in Cl. As the irrigation water leaches the soil and collects in Sump 120, the main differences are the increased total dissolved solids (shown on the solid bar in the center of the diagram) and higher levels of Na and Cl. Sinclair 4 brine is described by the third set of diagrams; the brine is characterized by high Ca, Na, K, and Cl. The brine has almost no SO_4 , unlike any of the surface waters in the area. The shape of the Stiff diagram for Sump 116 clearly shows that brine from Sinclair 4 is mixing with normal irrigation sump water; note the high Ca, Na, and Cl and the low

SO₄ in the sump water. The water in Vail 4A Drain downstream shows the same effects.

Trace elements are another way to detect brine pollution of surface waters. The bottom diagrams in Fig. 4 show B, Li, Mn, Sr, and Zn. All can be seen to be orders of magnitude higher in the Sinclair 4 brine than in surface water; they are also elevated in Sump 116 as expected and somewhat above background levels downstream in Vail 4A Drain.

The information from this case study has been useful in designing future monitoring programs to be carried out as geothermal development proceeds in the valley. The protection of beneficial uses is an important part of water quality management. The municipal water supplies in the valley (which come solely from irrigation canal water), agricultural supplies, and aquatic habitat are important beneficial uses that must be protected in the future in the Imperial Valley.

Toxicities, Costs, and Continued Monitoring

The IVEP is now in its transitional phase, which includes transferring future monitoring efforts to local agencies. In the past 2 years the IVEP has amassed an extensive baseline of environmental data from which future environmental assessments may be made. However, to cease making measurements on the brink of large-scale geothermal resource development would be a big mistake. For that reason we have proposed an ongoing monitoring program to be carried out by state and local geothermal regulatory agencies in order to monitor for changes in environmental quality in the future that may be caused by geothermal power development.

This program of ongoing sampling includes 40 water quality sampling sites to be sampled quarterly. To specify which chemicals are important to monitor on a continuing basis, we combined the results from our study of Vail 4A Drain with published toxicity data to come up with a minimum list of chemicals for analysis.

The three beneficial uses of municipal and domestic water supply, agricultural irrigation, and aquatic habitat have different lists of toxic chemicals that are important in water quality.

For domestic and agricultural purposes, the lists of toxic chemicals are well known and include such trace elements as Ag, As, B, Ba, Cd, Cu, F, Fe, Hg, Li, Mn, Ni, Pb, Se, and Zn.

For aquatic habitat, toxicity information is abundant but confusing because the toxicity of any

given trace element varies so much among fish species and depends greatly upon the chemical make-up of the water that the trace element is in. (For example, the hardness of the water and its pH affect toxicity of many trace elements.) However, for important fish species in Imperial Valley and from fish toxicity experiments carried out in water found in Imperial Valley, researchers in the IVEP have found that B, Cu, Li, Mn, and Zn might pose a threat to aquatic life in the Valley.

Costs of chemical analyses vary considerably from element to element, and for the chemicals we monitored in the IVEP, costs ranged from \$2.50 to more than \$25.00 per element. Thus, in any ongoing monitoring program, analyses costs will affect decisions on which element should be analyzed. This is especially true if one is trying to gain the most information from a water sample for the least cost.

Based on the typical costs of chemical analyses and the results from our baseline studies and case studies like the one in Vail 4A Drain, we suggest monitoring for the following lists of major constituents and trace elements to protect the valley's water resources during the development of geothermal power:

- Na, K, Ca, Mg, Cl, SO₄, CO₃, HCO₃, SC, TDS, pH, temperature.
- B, Li, Mn, Zn.

Arsenic, Se, Pb, and Ni deserve further study in the future since they may exist in high concentrations in some geothermal brines and since they are quite toxic. Mercury is very toxic, but has not been found in high levels in any of the brine data available to date; it has also been very low in all water samples we have taken in the valley.

Summary

These studies are important in documenting present water quality conditions in the valley and in identifying differences among geothermal brines in the various areas of the valley. The determination of a comprehensive data base of baseline water quality conditions before geothermal development begins is an important step in water quality management. Using these data, developers, regulators, and environmentalists can assess the impacts that geothermal development is likely to have on the valley's water resources in the future, as well as detect any changes that may occur by making similar measurements in future monitoring programs.

MIRROR FUSION-FISSION HYBRIDS OFFER VERSATILE ENERGY POTENTIALS

What is Fusion-Fission?

Fuse a deuterium (D) and a tritium (T) nuclei, and a 14-MeV neutron plus a 3.5-MeV alpha are produced. Fusion-fission is a concept for using such fusion neutrons to cause fertile materials to fission directly and/or indirectly. Direct fission of fertile material is possible because the kinetic energy of D-T fusion neutrons is high enough to excite ^{238}U and ^{232}Th to fission. Indirect fission occurs because high energy neutrons can generate additional neutrons via (n,fiss), (n,2n), (n,3n) and $^7\text{Li}(n,n\text{T})$ reactions. These excess neutrons, in turn, can convert fertile into fissile material. Excess neutrons are needed because for each D-T fusion neutron produced a triton (T) must be bred, all or mostly by $^6\text{Li}(n,\text{T})$ reactions.

All fusion-fission systems consist of fusion components producing, containing, and maintaining a fusion plasma and of a blanket that surrounds the plasma intercepting fusion neutrons. If net fissile material is produced in the blanket, the fusion-fission system may include separate fission reactors fueled with this fissile material.

Although other neutron-producing fusion reactors are possible (namely, D-D) the much higher cross section for D-T fusion at relatively low temperature makes D-T fusion the practical choice for fusion-fission.

Fusion-fission can be classified in a number of ways. One way is whether fission in the blanket is encouraged or suppressed. If fission in the blanket is encouraged, we classify it a "hybrid."¹ If blanket fission is suppressed, it is classified a "symbiosis."² Figure 1 outlines the principal nuclear reactions occurring in symbiotic and hybrid systems. With the hybrid we can fission the fissile material produced in separate fission reactors and/or in the blanket. We think the best use of the hybrid is production of excess fissile material for use in separate fission reactors.

Why Fusion-Fission?

Fusion as we currently conceive it is neutron rich but energy poor. Fission, on the other hand, is energy rich but neutron poor. We, therefore, think fusion and fission can complement each other to the benefit of both.

Fusion-fission benefits fusion because fission will increase energy release per fusion event which will improve power balance and/or power density.

This in turn reduces fusion technology requirements (lower magnetic fields, lower beam energies, lower component efficiencies) needed for economically competitive power generation. This will allow earlier commercialization of fusion and thus an earlier return on the investment in fusion research.

Fusion-fission could benefit fission in a number of important ways. Fusion-fission could eliminate fission's dependence on ^{235}U by converting the world's abundant fertile resources (^{238}U and/or ^{232}Th) to fissile fuel. This, in turn, could make present-day thermal fission reactor technology a long-term energy option. As an external source of neutrons, fusion-fission could provide the fissile material needed to make alternate fuel cycles practical. For example, ^{233}U -producing fusion breeders could be colocated with reprocessing plant(s) in secure international sites providing "denatured" fuel to national fission reactors. The "denatured" fuel could be ^{233}U plus ^{238}U or ^{232}U . Spent fuel would be returned to the international site for reprocessing. Any plutonium and other unwanted actinides produced in the fission reactors or in the fusion breeder could be consumed by recycling them through the fusion breeder. Fissile production can be independent of power generation and requires no initial fissile material inventory. Fusion-fission has no doubling time constraints; therefore, capacity can be built as rapidly as needed.

Blankets

A principal component of any fusion-fission system is the blanket that intercepts and uses fusion neutrons to produce tritium, fissile material, and energy. The blanket's role can vary from just producing fissile material to a nearly critical fission assembly just producing energy. Examples of blanket types covering this range are displayed in Fig. 2. The first two are nonfission blankets with anticipated net performances covering the range expected for blankets or symbiotic systems.

Net performance means the space- and time-averaged number of fissile atoms and energy removed from the blanket per fusion neutron. Energy production is listed as blanket energy multiplication (M), which is the ratio of energy produced in the blanket to fusion neutron kinetic energy (14.1 MeV). Tritium is also produced to fuel the D-T fusion reaction. The first² is dependent on $^7\text{Li}(n,n\text{T})$ reactions for excess neutrons while the second³ uses Be for neutron multiplication. A less

Fig. 1. Fusion-fission systems.

Blanket type	Net blanket performance (1)		
	${}^{233}\text{U}/n$	${}^{239}\text{Pu}/n$	M (2)
Symbiots			
• Li Th	~0.3	-	~1.0
• Be + Li + Th	~0.8	-	~1.6
Hybrids			
• U Li	-	1.5	11
• Th Li	~0.6	-	3.4
• U Th + Li	~0.7	0.6	~ 8
• U + Pu + Th + Li	> 1.0	< 0.5	> 10
• U + Pu Th + ${}^{233}\text{U}$ + Li + moderator	0	0	> 30

(1) Each case also produces 1.0 factors per D—T neutron.

(2) $M = E/n \div 14 \text{ MeV}$.

Fig. 2. Blanket types and anticipated performance.

expensive multiplier such as Pb could be used but performance would be less.

The rest of the blankets listed in Fig. 2 use fission for neutron and energy multiplication and are classified as hybrid blankets. All except the second hybrid blanket has uranium in the first zone to take advantage of $^{238}\text{U}(\text{n},\text{fiss})$, $(\text{n},2\text{n})$ and $(\text{n},3\text{n})$ reactions. The first two hybrid blankets are based on single fuel cycles (U or Th) and produce single fissile products (^{239}Pu or ^{233}U). The third hybrid blanket type combines the advantage of ^{238}U fast fission with the advantage of ^{233}U as a thermal reactor fuel. The fourth is similar to the third except that Pu produced in the U zone is recycled in that zone. The more Pu recycled the higher the ^{233}U breeding ratio and the blanket energy multiplication will be. The fifth hybrid blanket type is representative of fission blankets that produce energy, not fissile material. This blanket consists of a fast-fission U-zone-producing neutrons that drive a thermal lattice fission zone.

Our emphasis, to date, has been on uranium hybrid blankets. We have also looked at a thorium hybrid blanket.

The physical motivation for the hybrid is the fact that fast neutrons will cause the abundant fertile isotopes, ^{238}U and ^{232}Th , to fission with the resultant release of energy and neutrons. Infinite medium calculations show the actual theoretical potential for energy neutron multiplication of 14-MeV neutrons in uranium and thorium. Table 1 shows results of infinite medium calculations for natural uranium, ^{238}U , and thorium. Here, breeding reactions refer to (n,γ) reactions in ^{238}U and ^{233}U , respectively.

The energy multiplication and fissile breeding ratios predicted by the infinite medium calculations are exciting, but how good are such calculations? To partially answer this question, we have compared calculated and experimental results of a natural uranium pile.⁴ Table 2 shows results of this comparison. The pile was a 106-cm long, 99-cm-diam cylinder of 85% dense natural uranium with a 14-MeV neutron source at its center. The calculated

Table 2. Reactions per 14-MeV source neutron integrated over the Weale pile.

Reaction	Calculation	Experiment
$^{235}\text{U}(\text{n},\text{F})$	0.266	0.281 ± 0.017
$^{235}\text{U}(\text{n},\gamma)$	0.061	—
$^{238}\text{U}(\text{n},\text{F})$	1.11	1.18 ± 0.06
$^{238}\text{U}(\text{n},\gamma)$	4.36	4.08 ± 0.24
$^{238}\text{U}(\text{n},2\text{n})$	0.388	0.277 ± 0.008
$^{238}\text{U}(\text{n},3\text{n})$	0.195	0.327 ± 0.052
Leakage	0.504	0.42 ± 0.02

fission and $^{238}\text{U}(\text{n},\gamma)$ reactions both are within 7% of the measured experimental values. Based on this comparison we have some confidence in our ability to calculate hybrid blanket performance.

A thick pile of fertile material is not a hybrid blanket. There are numerous design considerations that must be addressed in order to develop a consistent blanket design. The important design considerations are: nuclear requirements, blanket geometry, refueling and replacement, tritium handling, heat removal, structural integrity, and materials. This list outlines topics that must be considered, all of which interrelate and affect nuclear performance.

There are two major nuclear requirements, tritium breeding and subcriticality. We believe the blanket should breed tritium sufficient to fuel the D-T fusion reaction. We also believe that the blanket should be subcritical under all conditions, both normal and abnormal. The blanket geometry must conform to plasma and magnets and allow for penetrations. A uniform current flux of D-T neutrons into the blanket is also very desirable. The blanket geometry must also allow for blanket refueling and replacement. Tritium removal and containment methods are important considerations because choices made effect tritium breeding rate needed as well as type and quantities of permeation barriers used in the blanket. Heat removal and structural integrity both effect the amount of structure needed. Blanket performance is quite sensitive to the ratio of structure to fuel because of competition for the neutron.

To get an idea of how blanket performance is affected by blanket requirements and design trade-offs, we compare a blanket's performance to that of an infinite medium.

Table 1. Infinite medium results (per 14-MeV neutron).

Material	Energy (MeV)	Breeding reactions (n,γ)
Uranium (natural)	309	5.0
^{238}U	233	4.4
Thorium	64	2.7

We found that requiring a uranium blanket to breed tritium and to contain structure results in a plutonium breeding ratio of 2.2 vs 5.0 and energy generation of 200 MeV vs 300 309 MeV compared to the infinite medium case. Both total breeding (tritium plus fissile) and energy generation are reduced one-third compared to the infinite medium.

Uranium metal has swelling problems at burn-ups and temperatures that are too low to be of much interest for hybrids. The effects of using ceramic forms of uranium fuel are significant. Uranium dioxides performance is half that of uranium metal, and uranium monocarbide is two-thirds of uranium metal. Since we are emphasizing fissile breeding, we do not need the high burnup and temperature capabilities of ceramic type fuels. We, therefore, are concentrating on metallic types of uranium fuels such as uranium 7 wt% molybdenum and uranium silicide. Performance with these fuels are about 25% below the uranium metal case.

Blankets consist of fuel contained in a pressure vessel of some form. Our conceptual hybrid blankets consist of many individual pressure vessels (or modules) containing a thorium or uranium fuel followed by tritium breeding lithium fuel. A major feature of these modules is a cylindrical pressure vessel capped by a hemispherical dome. To keep the thickness of this pressure vessel as thin as practical, the diameter of the modules are relatively small and the pressure vessels are cooled by the inlet coolant, in this case helium, at about 300°C. After cooling the hemispherical first wall, the coolant reverses direction and flows through the interior of the module and removes the nuclear heat generated in the fuel. Minimizing pressure vessel thickness, especially the first wall, is extremely important because the fusion neutrons must pass through this material before reaching the fertile fuel. A pressure vessel thickness of 0.5 cm (stainless steel) appears to be a reasonable compromise between nuclear performance and mechanical requirements.

Fission zone thickness is dictated by the required neutron leakage into the tritium breeding zone. Fission zone thickness varies between 20 and 30 cm for a blanket module of this type. Total blanket thickness is about 1 m.

Plasma containment dictates blanket geometry. The blanket must not intrude into the plasma volume and must allow for fueling and exhaust penetration. It is economically advantageous for the blanket to cover as much of the plasma as possible and to have a uniform D-T neutron current over its surface. For mirror confinement, a majority of the D-T neutrons are generated in a central spherical volume. To meet the objectives of high coverage and uniform current, the blanket is a spherical annulus surrounding the

central plasma volume and is inside the coils. The plasma is surrounded by radially aligned cylindrical modules, except for where penetrations are provided for fueling and plasma leakage fans.

As depicted in Fig. 3 the blanket forms a spherical annulus that surrounds the plasma and that has penetrations for fueling and leakage. The degree of blanket coverage used is dependent on thickness of the blanket coolant plena and shield, as well as plasma and coil geometries. Blanket performance is strongly affected by coverage.

Dropping coverage from 90 to 80% reduces fissile breeding and energy multiplication by about 40%. Performance is not linearly proportioned to coverage because tritium breeding must be maintained by increasing local tritium breeding. This is done by reducing the thickness of the fission zone.

An extremely important aspect of blanket design is accounting for exposure effects. To illustrate this point, Fig. 4 shows an example of the effects of exposure on a uranium monocarbide blanket. Exposure is measured in terms of integrated wall loading or energy current of 14-MeV neutrons across the first wall. M (blanket energy multiplication) is initially 8 and peaks at 32 after an exposure of 20-MW·y/m², a factor of four increase. The tritium breeding ratio (T) doubles after 20-MW·y/m². Pu, the net plutonium ratio, drops to 0 after an exposure of 24-MW·y/m².

These effects occur because the concentration of fissile plutonium and fission products builds up in the uranium. After an exposure of 20-MW·y/m² ²³⁹Pu concentration is 9% and the burnup is 12%. As stated earlier, we require the blanket to be subcritical (unable to support a fission chain reaction) under all conditions. As you can see by what happens to M (blanket energy multiplication), this blanket never goes critical. The fission neutron

Fig. 3. Reactor geometry.

Fig. 4. Uranium monocarbide blanket performance vs exposure.

multiplication factor K achieves a maximum value of 0.7 at 20-MW·y/m² exposure. K at 0 exposure is 0.3. Criticality by reconfiguration must also be avoided, and it is this that is expected to set an upper limit to exposure. Until reconfiguration scenarios are examined, we are setting an arbitrary upper limit on the fissile buildup of 4%. As it turns out, economics dictates the blanket be removed at fissile buildup of less than 3%.

The effects of fractional blanket coverage and exposure must be combined to determine effective blanket performance. Table 3 gives representative blanket performance for three fuels and various exposures. The last three columns of this table lists effective time average performance for blankets with three fuel types after various exposures. The first five columns list local instantaneous blanket values. In the UC fuel five-year exposure case, we see that as the local T breeding ratio increases from 1.05 to 1.43, the average blanket tritium breeding ratio is 1.05. Local M increases from 8 to 13.6 giving an average M of 9.18. Local net plutonium breeding decreases from 1.38 to 1.18 giving an average net plutonium breeding ratio of 1.09. At 5-year exposure, burnup is 1.5% and ²³⁹Pu buildup is 2.9%. As exposure continues, effective T breeding and energy multiplication increase while effective fissile breeding decreases.

The U-molybdenum case is representative of metallic fuels such as uranium silicide. The thorium case gives the lowest blanket performance, but the higher conversion ratio of ²³³U fuel in thermal fission reactors makes thorium competitive with metallic uranium fuel blankets. Combining the advantages of uranium and thorium in a single blanket should give the best performance.

Fissile accumulation in these three blankets are as follows. After an exposure of 5-MW·y/m², 1-m² of blanket accumulates 50 kg of plutonium for the U-molybdenum case, 35 kg of plutonium for the uranium carbide case, and 20 kg of ²³³U for the thorium case.

Table 3. Representative fast-fission blanket performance.

Fuel & exposure ^a	Local blanket values ^b					Blanket at equilibrium ^d		
	T/n	M	Pu/n	Burn up (%) ^b	Buildup (%) ^c	T/n	M	Pu/n
UC at 0 y	1.05	8.01	1.38	0	0	—	—	—
at 5 y	1.43	13.6	1.18	1.5	2.9	1.05	9.18	1.09
at 10 y	1.78	21.6	0.88	3.7	5.5	1.20	12.6	0.96
U-moly at 0 y	1.10	10.0	1.80	0	0	—	—	—
at 5 y	1.60	20.0	1.70	1.3	2.5	1.15	12.7	1.49
			(U/n)					(U/n)
Tw at 0 y	1.08	2.5	0.73	0	0	—	—	—
at 12 y	1.23	5.4	0.61	0.74	2.76	0.98	3.4	0.57

^aExposure at a first wall D-T neutron energy flux of 1.0 MW·y/m².

^bFission of heavy metal.

^cNet accumulation of fissile material in (%) of initial heavy metal.

^dTime-averaged performance of blanket with 85% coverage.

Fusion Driver

The central element of any fusion-fission system is the fusion neutron source. Fusion physics research programs have been underway since the early 50s. This effort is international in scope and has as its goal commercial fusion power.

The principal approaches to fusion being pursued are the Tokamak and mirror magnetic confinement fusion, and laser and electron beam heated inertial confinement fusion. Both magnetic and inertial confinement fusion are being studied as possible neutron sources for fusion-fission. Although this discussion is limited specifically to magnetic mirror systems, the energetics of mirror-based fusion-fission is representative of fusion-fission systems in general.

In all fusion systems, fuel must be heated to fusion temperatures and confined at a high enough product of density and time ($n\tau$) for significant fusion to occur. We call the ratio of fusion energy produced to energy invested in the plasma, Q .

The conceptual basis for magnetic mirror confinement fusion derives from the fact that energetic charged particles can be trapped on the field lines of a properly shaped magnetic field, provided the field is intense enough. In mirror machines, the field lines enter and leave the confinement zone through the chamber ends. Particle escape along the field lines is inhibited by intensifying the end fields. Particles approaching these regions (the mirrors) are then reflected, provided they are not directed too nearly parallel to the field lines. Escape through the mirrors occurs when interparticle collisions or other processes deflect a particle so that its vector is nearly parallel to the field lines.

Progress in mirror plasma physics experiments has been rapid within the last few years. The next generation mirror experiment MFTF scheduled for operation in 1981 is expected to achieve physics parameters close to a reactor-grade plasma. The major difference between the MFTF plasma and that required for a commercial reactor is physical size and duty factor; MFTF however is a sufficiently versatile experiment that it should establish scaling laws that will allow us to extrapolate to the larger plasma with a high degree of confidence. Also, $n\tau$ for the commercial facility is about a factor of 10 larger than in MFTF, this being a result of higher energy and the D-T isotopic mixture used in the commercial reactor as compared to MFTF. Thus, achievement of the anticipated plasma performance from MFTF will provide an adequate physics base from which development of a mirror hybrid could proceed.

Review of Mirror Hybrid Studies

Our work on the mirror hybrid concept started in the early 70s. This work started by examining the nuclear performance of blankets containing fertile materials.^{1, 5, 6} During this early stage we performed general scoping studies⁷ and completed our first reactor study. This study concentrated on a high M thermal fission blanket.⁸

In 1975 we performed our first conceptual reactor design study.⁹ This design had a fast fission uranium carbide blanket. Following completion of this conceptual design, we concentrated on optimization of mirror hybrid fusion-fission systems.^{10, 13} Results of these studies helped to convince us that fissile fuel production would be an attractive role for mirror hybrid reactors.

In 1977 we and General Atomic Company jointly performed a more detailed point design study of a ²³⁹Pu-producing standard mirror hybrid reactor.¹⁴

System Performance

The economic performance of a fusion-fission power system depends on the type and performance of the fusion driver, blanket, and fission reactors that comprise the system. As an example, here is an outline of our estimate of the performance of two systems; one based on the U/Pu fuel cycle, the other on the Th/U fuel cycle. Both use the standard minimum-B mirror as the fusion driver. The U/Pu based system is a uranium blanket producing make-up ²³⁹Pu for light water reactors (LWRs). The Th/U based system uses a thorium blanket producing make-up ²³³U for high temperature gas reactors (HTGRs). The blankets are the fast fission hybrid blankets (U-molybdenum and Th) described in the blanket section (Table 3).

Both hybrid reactors are optimized to minimize the cost of electricity from the fusion-fission system. Both are sized to have thermal power ratings approximately the same as present day fission reactors.

There are several significant parameter differences between the uranium and thorium blanketed systems. The uranium blanket, because of its high energy multiplication, results in a plant with a large electrical output. The thorium blanket reactor does not produce net electricity, just fissile fuel. Both blankets have about the same thermal rating, this being the result of a much larger fusion power output from the thorium blanket reactor as compared to the uranium blanket reactor. The high fusion power of the thorium blanket reactor is obtained by using a more intense magnetic field than for the uranium blanket reactor. The uranium

blanket reactor may, therefore, rely on existing NbTi superconductor magnet technology, whereas the thorium blanket reactor will require the more technologically advanced Nb₃Sn superconductor.

Both blankets produce between 2000 and 3000 kg of fissile fuel per year. However, the thorium blanket requires a rather high exposure, and the possibility of the blanket structure being able to attain $\sim 9 \text{ MW}\cdot\text{y}/\text{m}^2$ exposure is more uncertain. The average energy multiplication of the uranium blanket is about a factor of four higher than for the thorium blanket; these blanket multiplications include the effect of the fractional blanket coverage.

As a burner of Pu, we have used an LWR on a Pu recycle fuel cycle and supplemented with hybrid Pu. As a ²³³U burner, we have used a high-gain HTGR, using the thorium -²³³U fuel cycle.

The fissile production cost for the ²³³U- and ²³⁹Pu-producing hybrids are estimated at \$130 and \$55 per g, respectively. However, the lower fissile requirements of the HTGR as compared to the LWR results in approximately the same electricity cost from the two fission power plants. The breakdown of the fissile material costs indicate that they are dominated by capital costs. The fuel cycle costs account for fabrication, reprocessing and spent fuel shipping. Current (high) estimates for these services have been used, but they are not a dominant cost. For the uranium blanket reactor, approximately 60% of the plant revenues are generated by fissile production in contrast to the total revenue generated by fissile material for the thorium hybrid.

An important fission reactor economics is that the cost of producing fissile fuel in the hybrid (4.0 and 5.3 mills/kWh) is a small fraction of the total electricity cost. The conclusion is that the mirror hybrid reactor, based on a minimum-B mirror plasma confinement, is capable of converting the large fertile resources of the world into fissile fuel at a cost that does not strongly influence the net cost of electricity. A factor of two increase in fissile fuel generation costs (i.e., cost of the hybrid) would only increase electricity cost by about 20%. The uranium blanket hybrid supports 17 MWe per MW fusion while the thorium hybrid supports 9.

Reference Mirror Hybrid Reactor Design

Based on the results of our optimization studies and on successes in the mirror physics program, we spent 1977 developing a reference design of a mirror (fusion-fission) hybrid reactor.¹⁴ Our objectives were to conceptually design an early commercial facility for ²³⁹Pu generation based on near-term physics and technology.

To summarize the reference mirror hybrid design, we list the major design choices that have been made for the reactor.

- Minimum-B mirror confinement.
- Yin-Yang coil design, NbTi superconductor.
- Positive ion injectors with direct recovery.
- Fast spectrum blanket neutronics.
- Single-stage plasma direct converter.
- Cryocondensation vacuum pumping.
- Blanket:
 - U₃Si fuel (depleted U).
 - LiH tritium breeder (natural Li).
 - Inconel 718 structural material.
- He primary heat transfer loop (PHTL).
- Prestressed Concrete Reactor Vessel (PCRV):
 - Magnet restraint.
 - PHTL restraint.
 - Blanket support and restraint.
- Steam thermal conversion system.

The design approach we have selected is to mount the magnet, blanket and primary heat transfer loop all within a prestressed concrete reactor vessel (PCRV), of the type developed for gas-cooled fission reactors. This is shown in Fig. 5. In the center of the PCRV is the magnet and blanket, and the steam generators and He circulators are located around

Fig. 5. Fusion-fission mirror hybrid reactor.

the periphery. The blanket is a spherical shell inside the magnet. In this way, the blanket and its cooling system are locked together so that no relative motion between them can occur, thus precluding the possibility of rupturing any of the coolant ducts.

Table 4 lists the characteristics for the reactor.

LLL and General Atomic Company have chosen the reactor parameters to minimize the cost of producing fissile fuel for consumption in fission power reactors. As in the past, we have emphasized the use of existing technology where possible and a minimum extrapolation of technology otherwise. The resulting reactor may thus be viewed as a comparatively near-term goal of the fusion program, and we project improved performance for the hybrid in the future as more advanced technology becomes available.

Table 4. Reactor characteristics.

Fusion power	400 MW
Thermal power (av)	3600 MW
Injected neutral power	625 MW
Net electric output power	525 MW
First-wall 14-MeV neutron current	2 MW/m ²
Fissile production rate	2700 kg/yr
Injection energy D ⁺	125 keV
T ⁺	187 keV
β	0.7
Central ion density	9×10^{13} cm ⁻³
Q	0.63
n τ	2×10^{13} s/cm ³

Future Studies

For future mirror hybrid studies, we are planning to adopt new mirror confinement concepts and concentrate on ²³³U producing blankets. One such new confinement concept is the tandem mirror. Our predictions are that a low technology (8 T magnets and ~125-keV injectors) tandem might have a Q near 2 and a wall loading near 3 MW/m². Our past studies have indicated such Q's and wall loading should make an excellent fusion driver for a hybrid reactor. A tandem mirror experiment (TMX) is under construction at LLL to test the basic physics of the tandem concept. This experiment should be operating by the end of 1978.

We will concentrate on ²³³U producing blankets because of the importance placed on proliferation resistant fuel cycles. We believe such fuel cycles will only be practical if there is an external source of fissile material to supplement the poor neutron

economy expected of proliferation resistant fuel cycles.

Summary

The fusion-fission hybrid concept offers the potential of being a versatile method of making the vast energy potential of ²³⁸U and ²³²Th available to man, and doing so at a reasonable cost.

At Lawrence Livermore Laboratory, we have been studying hybrids based on magnetic mirror plasma confinement since the early 70's. This work started by studying the potential performance of hybrid blankets and has evolved to the point where we are now conceptually designing complete fusion-fission systems. These systems consist of mirror fusion components producing 14 MeV neutrons, fertile blankets in which the D-T neutrons provide energy and net fissile material, and fission burner reactors that convert this fissile material to energy. These studies indicate that one hybrid reactor can supply makeup fissile fuel for as many as 10 fission burner reactors of equal thermal rating and that the capital cost (\$/kWe) of such systems (fusion hybrid breeder + fission burner reactors) is only about 25% above the capital cost of thermal fission reactors alone.

Fusion hybrids could be a relatively near-term application of fusion research. Plasma experiments presently under construction, the Mirror Fusion Test Facility (MFTF) and the Tandem Mirror Experiment (TMX) scheduled for operation in 1981 and 1979, respectively, should come close to demonstrating plasma confinement needed for hybrid reactors.

In addition to expanding our fission energy resources manyfold, hybrids could offer the flexibility needed to make alternate fission fuel cycles practical.

The prospects for the fusion-fission hybrid are exciting and there is an expanding effort worldwide to quantify the hybrid's potential.

References

1. J. D. Lee, "Neutronics of Sub-Critical Fast Fission Blankets for D-T Fusion Reactors," in *Proc. 7th Conf. Intersociety Energy Conversion Engineering*, 1972 (American Chemical Society, 1972), p. 1294.
2. L. M. Lidsky, "Fission-Fusion Symbiosis: General Considerations and a Specific Example" in *Proc. of British Nuclear Energy Society Nuclear Fusion Reactor Conference at Culham Laboratory*, 1969, pp. 41-53 Culham Laboratory Report CLM-NFE. (1969)

3. J. D. Lee, et al., "Mirror Reactor Blankets," *Proc. of the Magnetic Fusion Energy Blanket and Shield Workshop*, 1976, pp. 539-556.
4. R. C. Haight, J. D. Lee, and J. A. Maniscalco, *Reaction Rates in a Uranium Pile Surrounding a 14-MeV Neutron Source: Calculations of the Weale Experiment*, Lawrence Livermore Laboratory, UCRL-77364 (1975). Also, NS&E, 61. 53(1976).
5. J. D. Lee, "Neutronic Analysis of a 2500 MWth Fast Fission Natural Uranium Blanket for a DT Fusion Reactor," in *Proc. First Topical Meeting on the Technology of Controlled Nuclear Fusion*, 1974 (San Diego, CA, 1974) CONF-740402-P1, Vol. 1, p. 233.
6. R. C. Haight and J. D. Lee, "Calculations of a Fast Fission Blanket for D-T Fusion Reactors with Two Evaluated Data Libraries," in *Proc. First Topical Meeting on the Technology of Controlled Nuclear Fusion*, 1974 (San Diego, CA, 1974), CONF-740402-P1, Vol. 1, p. 271.
7. R. W. Moir, "Conceptual Design Considerations for D-T Mirror Reactors With and Without a Fission Blanket," in *Proc. First Topical Meeting on the Technology of Controlled Nuclear Fusion*, 1974 (San Diego, CA, 1974) CONF-740402-P2, pp. 373.
8. W. C. Wolkenhauer, B. R. Leonard, Jr., A. M. Sutey, and R. W. Moir, "Conceptual Design of a Fusion-Fission Hybrid Reactor with a Subcritical Gas-Cooled Fission Blanket," in *Proc. First Topical Meeting on the Technology of Controlled Nuclear Fusion*, 1974 (San Diego, CA, 1974) CONF-740402-P1, pp. 238.
9. R. W. Moir, J. D. Lee, R. J. Burleigh, W. L. Barr, H. Fink, G. W. Hamilton, D. J. Bender, G. A. Carlson, W. L. Dexter, J. Holdren, C. L. Folkers, M. A. Peterson, M. E. Rensink, H. W. Patterson, R. L. Nelson, and C. E. Taylor, *Progress on the Conceptual Design of a Mirror Hybrid Fusion-Fission Reactor*, Lawrence Livermore Laboratory, UCRL-51797 (1975).
10. J. D. Lee, D. J. Bender, and R. W. Moir, "Optimizing the Mirror (Fusion-Fission) Hybrid Reactor for Plutonium Production," *Presentation to ANS Winter Meeting*, November 17, 1975, San Francisco, CA.
11. D. J. Bender and J. D. Lee, "The Potential for Fissile Breeding with the Fusion-Fission Hybrid Reactor," *Presentation to the ANS Summer Meeting*, June 14, 1976, Toronto, Canada.
12. D. J. Bender and G. A. Carlson, "System Model for Analysis of the Mirror Fusion-Fission Reactor," Lawrence Livermore Laboratory, UCRL-52293 (1977).
13. J. D. Lee, D. J. Bender, R. W. Moir, and K. R. Schultz, "Mirror Hybrids — A Status Report," *Proc. Second Topical Meeting on the Technology of Controlled Nuclear Fusion*, (1976) Richland, Wash., CONF-760935-P2, pp. 689.
14. D. J. Bender, J. D. Lee, W. S. Neef, R. S. Devoto, T. R. Galloway, J. H. Fink, K. R. Schultz, D. Culver, R. Rao, and S. Rao, "The Mirror Hybrid (Fusion-Fission) Reactor," *Proc. IAEA Conf. & Workshop on Fusion Reactor Design* (1977), Madison, Wisconsin. Proc. in preparation.

IMPACT TEST OF B77 MEASURES DYNAMIC BUCKLING OF TITANIUM AFTERBODY

The B77 is designed to withstand severe laydown impacts in any mode followed by secondary impacts on rebound. In its primary laydown delivery mode, the bomb will impact on or near its nose. The collapsible nose section is designed to cushion this impact. However, during tests we have observed that several significant secondary impact modes are possible. A severe impact sequence for the B77 is a lateral impact on a hard target followed by an axial impact on the tail. We observed a sequence in which a tail impact occurs when the forward end of the bomb strikes an object, the bomb rotates, and the tail impacts a structure.

We conducted a parametric study on the relationships among the acceleration loading on the B77 nuclear package, the afterbody buckling characteristics, and the impact velocity. This study, which used the SHOCK code, showed that for a given afterbody buckling load-deflection curve, the acceleration loading on the nuclear package increases with increasing impact velocity to some critical velocity (V_c) and then decreases. This parametric study also showed that V_c and the peak acceleration load on the nuclear package are directly proportional to the load at which the afterbody initially buckles.

We have analytically predicted the buckling behavior of the afterbody using the NSAP-2D (now called NIKE-2D) finite-element code. A full-scale buckling test was required to measure the dynamic buckling characteristics of the B77 afterbody for comparison with calculational results.

Description of the WRC 906 Impact Test Unit

The impact test unit (designated WRC 906) consisted of an instrumented, shortened buckling mockup of the titanium afterbody bolted to a steel cylindrical section with mass equal to the mass of the B77 with the parachute deployed. Figure 1 shows a photograph of the unit at the Site 300 drop tower.

The Sandia-designed titanium afterbody has an upper conical section (3.4-mm wall thickness), which tapers down to a cylindrical section (2.7-mm wall thickness). Four aluminum Tee Fins are doweled and bolted to the lower cylindrical section. Because of the expense of making a full-sized afterbody, we decided to make two shortened buckling mockups of the afterbody using one Sandia-supplied titanium

Fig. 1. Impact test unit at the Site 300 drop tower.

forging; one part would be used in WRC 906 and the other in a later full-scale tail impact unit. Shortening the length (both conical and cylindrical sections were reduced by half) should not significantly affect the buckling behavior, which is primarily a function of the mean diameter, wall thickness, and material properties.

The B77 mass mock consists of a 40-mm wall steel pipe welded to an 85-mm-thick end plate, which is in turn bolted to the afterbody. Angle brackets bolted to the pipe hold Teflon bushings for guiding the unit on the drop tower cables. The measured weight of the test unit without the afterbody is 1020.6 kg.

Test Conditions

We conducted the WRC 906 impact test at the drop tower facilities located at Site 300, building 858. The test unit was released from a height of 4.26 m and achieved an impact velocity of 9.14 m/s with the impact being flat within 1 mm. The unit impacted an 880-kg steel cylinder secured to the drop facility's 76-mm-thick steel impact plate. The unit was stabilized at ambient temperature prior to the test.

Instrumentation

The information required from the test was the dynamic load-deflection curve of the buckling afterbody. In several key areas, we used redundant techniques to assure complete data acquisition. Strain gages (biaxial) mounted on the outer surface of the afterbody above the calculated buckling area, measured the loading history on the afterbody. We performed a static load-deflection test on the afterbody prior to the drop test to calibrate the strain gages.

Accelerometers, mounted on the bottom plate of the pipe weldment mass mock, measured its acceleration history. These acceleration data could be used with the appropriate mass value as an additional method of measuring the force on the afterbody. Double integration of these accelerometer signals also provided a backup displacement history at the top of the afterbody.

The displacement history of the top of the afterbody (bottom of welded end plate) was measured directly with a displacement transducer mounted on a pedestal located on the impact anvil. The transducer was positioned so that its 25 mm of linear range began when the afterbody made contact with the impact block. The mounting pedestal for the transducer was slotted so that it would easily buckle when the end plate impacted on the transducer head.

Two velocity-timing stands were located adjacent to the impact block. Each stand held three horizontal graphite rods spaced 152 mm apart. As each rod was broken by a projection from the falling unit, an electrical pulse was triggered and recorded. We calculated the velocity from the timing of the successive pulses.

A thin wire string 13 mm above the impact surface served as a switch to fire a fiducial signal. It triggered a signal pulse on all data channels and fired bridgewires that could be seen in the high speed films to correct for timing errors between data channels.

Six copper impact switch strips were placed on the impact block in a radial pattern. The impact flatness was determined from the switch sequence timing and impact velocity.

The drop test was photographed with five high speed cameras. Four closeup cameras operating at a film speed of 4000 frames per second covered views of the impact area and the afterbody from two directions, 90° apart. An overall view of the drop was filmed at 400 frames per second.

Test Results

The afterbody buckled as expected and the instrumentation and high speed cameras performed successfully. Figure 2 shows the buckled afterbody.

The data from the velocity timing stands indicated an impact velocity of 8.94 m/s. However, the high speed camera films, which we judge to be more accurate, gave a velocity of 9.14 m/s.

We obtained the time history of the axial load on the afterbody from the average of the strain histories measured by the four axial strain gages located above the predicted buckling area. Figure 3 shows the average strain trace that was used to obtain the loading histories.

We measured the first 25 mm of displacement of the afterbody's upper surface by the displacement transducer mounted on the impact block. This

Fig. 2. Buckled afterbody after impact test.

Fig. 3. Average strain gage results were above predicted buckling area.

measurement is terminated when the weldment plate impacts the transducer probe. Displacement was also determined by double integration of the average accelerometer signal measured on the pipe. Figure 4 shows the good agreement that was obtained from these two separate displacement determinations. The displacement trace calculated from the acceleration history was slightly higher since it also included the motion of the impact block.

Figure 5 gives the afterbody dynamic load-deflection curve produced by cross plotting the displacement measured by the transducer and the force determined from the average strain history. The initial portion of the test curve was obscured by an erratic second fiducial signal (Fig. 3), and the curve shown in Fig. 5 was produced by extending the upper linear portion and shifting the curve to pass through the origin. If there were a lower stiffness portion of the curve in the area masked by the fiducial signal, the test curve would shift along the deflection axis to show better agreement of the initial slope (afterbody elastic stiffness) with the calculated curve. The calculated elastic stiffness was in good agreement with the value obtained from the static load-deflection test conducted to 0.4 MN. The measured buckling load of 2.75 MN was 19% lower than the calculated value, which is in very good agreement for a buckling problem.

Fig. 4. Comparison of data from two measurement techniques.

Still pictures made from the films show the buckling dynamics of the afterbody. As seen in Fig. 6a, buckling began at the intersection of the cylindrical and conical portions of the afterbody. Both circumferential and axial waves were formed, creating the diamond surface pattern, which is classical for this type of thin shell buckling. In Fig. 6b, the amount of deformation has increased and the formation of plastic hinges at the ridges and valleys can be seen. Figures 6c and 6d show the fracture of the hinges, and Fig. 6e shows the expulsion of the fractured half-diamond pieces and the interlocking of the serrated edges. The total change in height of the afterbody was 80 mm.

Fig. 5. The measured afterbody load-deflection curve shows a lower buckling load than the calculated value.

Conclusions

We have made three general observations from the test:

- The afterbody performed during the impact test as a buckling, frangible mitigator, absorbing the kinetic energy of the impacting test unit.
- The afterbody buckled as predicted with the measured and calculated buckling loads showing very good agreement.
- The 19% reduction of the afterbody buckling load will result in a reduction in the expected peak g-load for the nuclear package.

The last conclusion will be verified by the full section tail impact test and by direct calculations using the test results. The results will also be used in the SHOCK code to determine the worst-case impact velocity (V_c) for the full section tail impact test.

Fig. 6. Buckling dynamics of the afterbody as seen in still pictures made from high speed films.

TECHNICAL NOTES

Automatic Tube Welder Used for Geothermal Application (*C. E. Walter, Material Fabrication Division*)

Recently, the Materials Fabrication Division (MFD) assisted Earth Sciences personnel in fabricating a 1.22-km-long tube for use with a pressure transducer for the Salton Sea geothermal wells in Southern California's Imperial Valley. In service, the tubing would be subjected to severe corrosion and high temperatures. In the wells, particulate levels of 300,000 ppm brine are seen with chloride levels of 170,000 ppm and operating temperatures of 260°C.

For this application, we joined 0.31-km lengths of Hastelloy C276 tubing to provide a tube of the required length. The tubing, selected for its heat and corrosion resistant properties, had an o.d. of 3.30 mm and an i.d. of 1.52 mm. The need was for a full penetration weld joining the 0.31-km lengths, but with minimum restriction of the i.d. of the tubing.

To accomplish this difficult welding task, we used our newly acquired automatic tube welding system. The system, manufactured by Magnatech of East Granby, CT, consists of a welding head, small tubing adapter and an integral controller/programmer assembly mated with Centaur 75-A welding power supply manufactured by Dimetrics, Inc., of Sepulveda, CA. We purchased this new equipment to support weapons programs as well as any other program where it can be effectively applied.

Prior to welding the 0.31-km lengths, we did some weld procedure development work. A sample weld in a 3.1-m section of tubing was given to the Earth Sciences Division to be tested for strength and corrosion resistance in the geothermal wells. During the week of April 3, 1978, the 0.3-km coils of tubing were brought to the precision weld room in building 321 where the welds were made. A sample weld was made at the same time and subjected to burst testing. The sample tube ruptured at a pressure in excess of 468.85 MPa at several centimeters away from the weld.

The 1.22-km length of welded tubing has been installed in a geothermal well, and the pressure transducer operated without any problems.

We are increasing the capability of the automatic tube welding system by adapting a 300-A welding power supply to be used where higher amperages are required. We expect the automatic system will be used to solve many welding problems

where high quality welds are necessary in difficult-to-weld applications.

Diffusion Bonding of Havar Foils to Stainless Steel Substrates (*J. C. Swingle and S. B. Brown, Energy Systems Engineering Division*)

The pursuit of repetitively pulsed lasers pumped by electron beams requires the advent of metal foil and support structures capable of operation at elevated temperature for extended periods of time.

Techniques such as laser welding, electron beam welding, brazing, and diffusion bonding have been considered by many as options for the attachment of the foil to the support structure.

During the last year, we have studied the diffusion bonding of the cobalt alloy Havar (42Co, 23Fe, 20Cr, 13Ni, 2Mo) to stainless steel substrates. Havar represents an interesting material as an electron transmission window for systems such as gas lasers, which have a pressure differential across the foil. The tensile strength of Havar exceeds 2.07 GPa and can be used at temperatures up to 540°C.

We found that an intermediate material, such as nickel, placed between foil and substrate caused excellent diffusion bonds. We also found that pressures of 13.8 MPa in the bond area were sufficient to achieve bonding at 520°C. The foil thickness was 2.5 μm .

There was no wrinkling of the foil on samples of 4-cm² area. This is to be expected since the thermal-induced stresses introduced in the bonding process are not sufficient to produce yielding of the foil. However, nickel foils wrinkled under these conditions.

During the next year, we plan to use foil that will be 10 times thicker to create structures of 100 times greater area.

Vane-Axial Fan Design for Closed-Cycle, Rare-Gas Halide Lasers (*J. C. Swingle and J. W. Dickie, Energy Systems Engineering Division*)

Rare-gas halide lasers have emerged in recent years as efficient sources of intense ultraviolet radiation. The radiation is produced by diatomic molecules formed by the binding of a rare-gas atom to a halogen atom. The radiation can also be produced in various spectral bands across the ultraviolet because of the many permutations of the candidate atomic species. These species are included

among the class of "excimers," a group characterized by very weak chemical binding and spontaneous dissociation in the ground configuration, whereas the excited state configurations possess significant chemical binding leading to stable molecular species until such time as radiation of collisional deactivation occurs. The rare-gas halide-excited states possess a strong ionic bonding character analogous to the alkali halides.

We have operated laser devices using rare-gas halides at peak fluences of about 10 MW/cm². The most intense research effort has centered on the rare-gas fluorides to date.

Gas mixtures containing <1% F₂ with rare gases have been studied when excited by electric discharges or electron beams, or both. The presence of fluorine, even in such low concentrations, has presented some serious material compatibility problems to the laser designer. We are now attempting closed-cycle operation of these devices, which again raises the material compatibility question with regard to the average power that the device must dissipate and the long-term effect of system components on the purity of the circulating gas mixture.

One particularly important problem involves the isolation of the fan motor from the working gas. Since these systems must be evacuated before the gas mixture is introduced to the flow loop, we must find a means of isolating the fan motor when it is stationary, as well as when it is running.

Figure 1 shows the design features intended to solve these problems in a closed-cycle rare-gas halide laser now being operated in Building 171. The fan

motor is housed in a sealed can that is supported as a centerbody in a 15-cm-diam stainless-steel duct. During evacuation of the flow loop, an air-driven bellows is extended to make an O-ring seal against the back surface of the impeller centerbody. Then the laser gas mixture is introduced to the system and a helium buffer gas is injected around the fan shaft where it penetrates the housing. This buffer gas flow goes into the fan housing, thus isolating the two volumes from each other. The buffer gas flow rate is controlled by electronic manometers so that the amount of helium expended can be minimized. The buffer gas injected into the laser system becomes part of the gas make-up flow, which is necessary to recondition the gas mixture.

Nondestructive Evaluation of the Thermal Stabilizer Solder Bond in the Superconducting Magnet for the Mirror Fusion Test Facility (MFTF) (B. J. McKinley, Materials Engineering Division)

Magnetic fusion uses a magnetic field for plasma confinement. The plasma energy density increases with magnetic field, which means that both the size and cost of a commercially practical fusion reactor will be reduced if large fields are used. The most economical way to generate these fields, which are about 100,000 times stronger than the earth's magnetic field, is with superconducting magnets. The new MFTF (see ME Quarterly, UCRL-50016-77-3) will require magnets many meters in size with a conductor capable of carrying many thousands of amperes of current.

The conductor that we developed for this magnet construction is itself a compound structure designed to dissipate the small amounts of heat that are occasionally generated in the superconductive core of the conductor. Figure 2 shows the outer copper stabilizer, partially unwrapped from the 1-cm square superconductive core. The final operation in conductor fabrication consists of soldering the stabilizer to the core.

During preproduction tests, it became evident that there was considerable difficulty in achieving an adequate solder bond. A good bond is essential for proper functioning of the magnet. Consequently, we decided to implement 100% inspection of solder bond in this conductor.

Feasibility studies initiated in August 1977 indicated that ultrasonic inspection could distinguish soldered from unsoldered regions. We were requested to develop a bond test and certification procedure based upon these initial studies.

The specification for acceptable bonding was established by correlating the metallographic

Fig. 1. Design features of vane-axial fan for a closed-cycle, rare-gas halide laser.

Fig. 2. Superconductor with stabilizer partially stripped off.

evaluation of bond integrity with the amplitude of the ultrasonic reflection from the bond interface. The reflection from the cooling grooves adjacent to the bond are used as a reference. If the bond interface reflection is less than 60% of the amplitude of the reflection from the cooling groove, the bond is acceptable.

A test coil is being made to check the acceptability of the stabilized superconductor design. We inspected about 2 km of stock for the coil at the vendor. Ultrasonic data from that material was used to establish the following specification.

Superconductor Certification of MFTF. All the stabilized superconductor stock for the two MFTF coils will be inspected at the vendor and reinspected at LLL during the winding operation. Each coil contains about 21 km of stock for a total of 66 million solder bonds to evaluate and document. The specification for unacceptable unbond density and distribution is as follows:

- Greater than eight consecutive unbonded lands on any one side, or
- Thirteen unbonded lengths accumulative over all four sides in any 7.19-cm length, or
- Twenty-seven unbonds accumulative over all four sides in any 1.5-m length.

We are outlining a plan to make this complicated decision automatically with an on-line mini-computer.

About 120 joints or "splices" will be made in each coil. We do not plan nondestructive evaluation

of the cold-weld in the core. However, inspection of the stabilizer section, added to cover that joint, is required. This will be a manual scanning operation with the operator making the evaluation based on interpretation of the reflections seen on a cathode ray tube (CRT).

Developments and Test Schedules. We had both the vendor's and our new system operating in our laboratory primarily for the purpose of training three ultrasonic inspectors. LLL will have a two-shift winding operation requiring a full time inspector on each shift. We will also train one person from the vendor's staff. They must be certified Level II Inspectors based on requirements established by The American Society for Nondestructive Testing. For a specific job such as this, the training can be accomplished in about 3 weeks.

The electronics for the LLL ultrasonic data acquisition system is similar to the system developed for the vendor. The new water cells used to hold the transducers (Fig. 3) are being fabricated. The vendor required some alterations, and we designed a special "sky-hook" fixture for ours, which allows the water cell to move with the stock as it comes off the reel. We also designed and built the computer controlled data interpretation and wrote the software for it.

A qualifying run was started in October 1978, to check out the vendor's new line, including the ultrasonic inspection. LLL had a practice wrapping period in August and September and will start the first coil in October. The second coil is scheduled for completion in November, 1979.

Fig. 3. Five-channel ultrasonic system and water cell used in coupling ultrasound between the transducers and superconductor.

PUBLICATION ABSTRACTS

R. H. Toland and T. T. Chiao, *Stress-Rupture Life of Kevlar Epoxy Spherical Pressure Vessels*, Lawrence Livermore Laboratory, UCID-17755, Part 2 (1978).

We are conducting a study to determine the life of Kevlar/epoxy spherical pressure vessels subjected to a constant, sustained pressure until vessel failure, i.e., stress-rupture. This study has two objectives: to generate baseline data on the stress-rupture life of Kevlar/epoxy pressure vessel and to apply statistical reliability theory to vessel and strand data to define vessel life statistics and reliability at given pressure (stress) levels. This report, the second of three, is a compilation of the current pressure vessel data to-date and all strand stress-rupture data generated at Lawrence Livermore Laboratory on several composite materials.

J. J. Lim and J. E. Wells, *Aesop: A Computer Program for Resource Scheduling and Leveling*, Lawrence Livermore Laboratory, UCID-17775 (1978).

This report illustrates how the computer program AESOP can assist in allocating resources effectively in a multiproject system and provides information on how to use the program.

R. H. Carpenter, *Horizontal Gas-Tungsten Arc Welding of 0.020-in. (0.5-mm) 1100 Aluminum*, Lawrence Livermore Laboratory, UCID-17780 (1978).

This report describes the procedure developed by the LLL Metals and Ceramics Division's Weld Development Laboratory for butt-welding 0.020-in. (0.5-mm) 1100 aluminum horizontally by means of the gas-tungsten-arc process. The depth of penetration was 100%, and sectioning showed the nugget to be free of porosity and other defects.

S. J. Sackett, *JASON - A Code for Solving General Electrostatics Problems, User's Manual*, Lawrence Livermore Laboratory, UCID-17814 (1978).

D. Bender, *The "Best" ²³³U-Producing Blanket for the Tandem Mirror Hybrid*, Lawrence Livermore Laboratory, UCID-17823 (1978).

W. Lai, *Gas Laser Cells — Stress Analysis of Cylindrical Cells with Radial Injection of Electrons*, Lawrence Livermore Laboratory, UCID-17850 (1978).

T. J. Altenbach, *Interim Report on Nuclear Waste Depository Thermal Analysis*, Lawrence Livermore Laboratory, UCID-17865 (1978).

A thermal analysis of a deep geologic depository for spent nuclear fuel is being conducted at LLL as part of the NRC Nuclear Waste Management Program. The TRUMP finite difference heat transfer code is used to analyze a 3-dimensional model of the depository. The model uses a unit cell consisting of one spent fuel canister buried in salt beneath a ventilated room in the depository. A base case was studied along with several parametric variations. It is concluded that this method is appropriate for analyzing the thermal response of the system, and that the most important parameter in determining the maximum temperatures is the canister heat generation rate. The effects of room ventilation and different depository media are secondary. Future work will extend this analysis and improve upon some of the simplifications used.

J. K. Meier, *Thermal Analyses of the IF-300 Shipping Cask*, Lawrence Livermore Laboratory, UCID-17895 (1978).

P. A. House, *Performance Tests of the Radial Outflow Reaction Turbine for Geothermal Applications*, Lawrence Livermore Laboratory, UCID-17902 (1978).

A unique pure reaction turbine, for geothermal applications, has been developed at the Lawrence Livermore Laboratory. This radial outflow reaction turbine (RORT) is designed specifically to produce power from the expansion of saturated or compressed liquid at temperatures of less than 180°C.

In the tests reported here the highest efficiency measured was 32.7%, clearly below the peak efficiency for this small machine. Extrapolations to larger machines indicate that an efficiency near 50% is a credible goal, an attractive performance as either a Total Flow expander for liquid or in conjunction with conventional flashed steam systems. A rough cost estimate indicates that a 7.5 MW RORT would cost somewhere between 0.5 M\$ and 1.5 M\$, and could add about 15% increase in the power output of a conventional 50 MW plant. This means that for less than a 3% increase in capital cost the bus bar energy cost can be reduced by about 10%. Another important result is that the RORT is uniquely suited for conversion of the thermal and pressure energy

components in the geopressed resources. The development and proof of feasibility of efficient liquid expanders broadens the opportunities for economic power production from lower temperature geothermal resources, and possibly utilization of waste heat in industrial processes.

R. G. Dong, *Effective Mass and Damping of Submerged Structures*, Lawrence Livermore Laboratory, UCRL-52342 (1978).

Various structures important for safety in nuclear power plants must remain functioning in the event of an earthquake or other dynamic phenomenon. Some of these important structures, such as spent-fuel storage racks, main pressure-relief valve lines, and internal structures in the reactor vessel, are submerged in water. Dynamic analysis must include the force and damping effects of water. This report provides a technical basis for evaluating the wide variety of modeling assumptions currently used in design analysis. Current design analysis techniques and information in the literature form the basis of our conclusions and recommendations. We surveyed 32 industrial firms and reviewed 49 technical references. We compare various theories with published experimental results wherever possible. Our findings generally pertain to idealized structures, such as single isolated members, arrays of members, and coaxial cylinders. We relate these findings to the actual reactor structures through observations and recommendations. Whenever possible we recommend a finite way to evaluate the effect of hydrodynamic forces on these structures.

W. Lai and E. W. McCauley, *Air Scaling and Modeling Studies for the 1/5-Scale Mark I Boiling Water Reactor Pressure Suppression Experiment*, Lawrence Livermore Laboratory, UCRL-52383 (1978).

Results of table-top model experiments performed to investigate pool dynamics effects due to a postulated loss-of-coolant accident (LOCA) for the Peach Bottom Mark I boiling water reactor containment system guided subsequent conduct of the 1/5-scale torus experiment and provided new insight into the vertical load function (VLF).

Pool dynamics results were qualitatively correct. Experiments with a 1/64-scale fully modeled drywell and torus showed that a 90° torus sector was adequate to reveal three-dimensional effects; the 1/5-scale torus experiment confirmed this. Table-top scaling-law studies showed (and 1/5-scale torus experiments also confirmed) that the VLF is insensitive to the enthalpy flux parameter. Addi-

tionally, table-top experiments produced data suitable for computer code verification.

Table-top, 1/5-scale torus, and other scaled experiments show an oscillatory VLF; the maximum download is typically double-spiked, whereas the maximum upload is more gradual. The load function contains a high frequency oscillation superimposed on a low frequency one; evidence from measurements and from momentum modeling with a computer indicates that the oscillations have hydrodynamic origins.

The maximum download diminishes with initial downcomer fill level. When the downcomer is initially empty, table-top experiments show that the maximum download degenerates to a sinusoidal shape. This leads to the possibility of decomposing the VLF into a low-frequency-damped sinusoidal load plus a higher frequency (~10 times the low frequency) damped sinusoidal load.

B. J. Kowalskie, *A User's Guide to Designing and Mounting Lenses and Mirrors*, Lawrence Livermore Laboratory, UCRL-52411 (1978).

This guidebook is a practitioner-oriented supplement to standard tests in optics and mechanical engineering. It reflects the author's practical experience with the oftentimes troublesome aspects of effectively integrating optical components with mechanical hardware. Accordingly, its focus is on the techniques, assumptions, and levels of design sophistication needed for a wide variety of sizes and optical surface quality levels. It is intended to be a primer for engineers, designers, and draftsmen already familiar with some of the problems encountered in mounting optical components and who are responsible for developing components for high-energy laser systems.

J. O. Hallquist, *DYNA2D — An Explicit Finite Element and Finite Difference Code for Axisymmetric and Plane Strain Calculations (User's Guide)*, Lawrence Livermore Laboratory, UCRL-52429 (1978).

DYNA2D is an explicit two-dimensional plane strain and axisymmetric Lagrangian finite element and finite difference code. Spatial discretization may be accomplished by constant-stress elements that can be degenerated to triangular zones, constant pressure variable-node elements, nine-node Lagrange elements, or finite difference zones based on the HEMP difference equations. A general slide-line capability is implemented that admits frictional sliding along arbitrary, intersecting grid lines.

Gravity effects are accounted for in the initialization whenever needed, as in soil-structure interaction problems. Loading functions admit pressure and shear loadings along a boundary, body force loadings due to spinning and base accelerations, and nodal velocity-time histories.

D. L. Margolis, *An Analytical Study of Intake Tuning for Helical-Rotor Expanders*, Lawrence Livermore Laboratory, UCRL-52449 (1978).

A mathematical model of a circular lobed helical-rotor expander has been modified to include dynamic interactions with the intake plumbing. Parametric studies were made to determine the effects of these dynamics on overall expander performance. Variations in the intake geometry produced substantial variations in expander output power for a given steady-state rotor speed; however, actual supercharging using passive intake tuning was not possible.

P. A. House, *Analysis of a Radial-Outflow Reaction Turbine Concept for Geothermal Application*, Lawrence Livermore Laboratory, UCRL-52480 (1978).

Described herein is the radial-outflow reaction turbine, a pure-reaction turbine designed to improve the conversion efficiency of geothermal energy into electrical power. It also has potential as a total-flow turbine for low-temperature water. We can use the principle of incomplete expansion to obtain a reduction in turbine size when the turbine exhausts into a low-pressure condenser. And, by adding this turbine to single- and two-stage flashed-steam systems, we can improve the conversion efficiency of systems utilizing low- and high-energy wellhead sources, respectively. The Appendix outlines our analysis of the radial-outflow reaction turbine and leads to an expression for engine efficiency.

B. O. Sellick, Sr., *Diffraction Efficiency and Relative Intensity of Various X-Ray Analyzing Crystals at $Cu_{K\alpha}$ and $Sn_{K\alpha}$ Wavelengths and with Two Surface Conditions*, Lawrence Livermore Laboratory, UCRL-52516 (1978).

Crystals used for x-ray analysis come in many useful planes and 2d spacings with great variation in diffraction efficiency. This report compares the diffraction efficiency of 13 different crystals at two wavelengths, $Cu_{K\alpha}$ and $Sn_{K\alpha}$, and with two surface conditions, first with a cleaved or polished surface and second with a ground or sandblasted surface for

enhanced diffraction. It is not obvious from published information how to select a crystal for best detection efficiency for a given plane or 2d spacing. The information in this report should help users select a crystal for a specific application.

T. W. Alger, *Droplet Phase Characteristics in Liquid-Dominated Stream-Water Nozzle Flow*, Lawrence Livermore Laboratory, UCRL-52534 (1978).

An experimental study was undertaken to determine the droplet size distribution, the droplet spatial distribution and the mean droplet velocity in low-quality, steam-water flow from a rectangular cross-section, converging-diverging nozzle. A unique forward light scattering technique was developed for droplet size distribution measurements. Droplet spatial variations were investigated using light transmission measurements, and droplet velocities were measured with a laser-Doppler velocimeter (LDV) system incorporating a confocal Fabry-Perot interferometer. Nozzle throat radius of curvature and height were varied to investigate their effects on droplet size.

Droplet size distribution measurements yielded a nominal Sauter mean droplet diameter of 1.7 μ m and a nominal mass-mean droplet diameter of 2.4 μ m. Neither the throat radius of curvature nor the throat height were found to have a significant effect upon the nozzle exit droplet size. The light transmission and LDV measurement results confirmed both the droplet size measurements and demonstrated high spatial uniformity of the droplet phase within the nozzle jet flow. One-dimensional numerical calculations indicated that both the dynamic breakup (thermal equilibrium based on a critical Weber number of 6.0) and the boiling breakup (thermal nonequilibrium based on average droplet temperature) models predicted droplet diameters on the order of 7.5 μ m, which are approximately equal to the maximum stable droplet diameters within the nozzle jet flow.

W. Lai and E. W. McCauley, *Modeling Vertical Loads in Pools Resulting from Fluid Injection*, Lawrence Livermore Laboratory, UCRL-80645 (1978). Submitted to Symposium on Fluid Transient and Acoustics in the Power Industry, 1978 Winter Annual Meeting, ASME, San Francisco, CA, December 10-15, 1978.

Table-top model experiments were performed to investigate pressure suppression pool dynamics effects due to a postulated loss-of-coolant accident (LOCA) for the Peachbottom Mark I boiling water

reactor containment system. The results guided subsequent conduct of experiments in the 1/5-scale facility and provided new insight into the vertical load function (VLF).

Model experiments show an oscillatory VLF with the download typically double-spiked followed by a more gradual sinusoidal upload. The load function contains a high frequency oscillation superimposed on a low frequency one; evidence from measurements indicates that the oscillations are initiated by fluid dynamics phenomena.

The maximum download diminishes with initial downcomer fill level. When the downcomer is initially empty, the maximum download degenerates to a gradual sinusoidal shape. This leads to the possibility of an empirical model of the VLF consisting of damped low frequency and a higher frequency (~ 10 times the low frequency) sinusoidal components.

As evidenced by the 25 air-water tests conducted with our 1/5-scale three-dimensional facility, the VLF measured from the table-top experiments accurately predicted the general characteristics of the VLF from larger, properly configured apparatus.

I. F. Stowers and H. G. Patton, *Cleaning Optical Surfaces*, Lawrence Livermore Laboratory, UCRL-80731 (1978). Presented at the Conf. Optical Coatings, Society of Photo-Optical and Instrumentation of Engineers, Washington, D.C., March 28-29, 1978.

The advent of very large laser systems with thousands of optical components has necessitated an investigation of methods for cleaning both coated and uncoated optical elements.

To perform adequately in laser systems, optical surfaces must be free from both films and particulate matter. Films have undesirable absorption bands and particles scatter light. Furthermore, in high power laser systems contaminants on the surface or trapped between the layers of coatings are known to lower the damage threshold. All surfaces must therefore, be clean when the optical elements are coated and installed and must remain clean for years after installation.

Accomplishing this goal of long term cleanliness requires detailed consideration of cleaning methods and all mechanisms of recontamination. Generally, the nature of contaminants are unknown and therefore several cleaning steps may be necessary. Many conventional cleaning methods have proven unsuitable because they damage the precision surfaces they are to clean. Once cleaned, optical elements must be handled in such a manner as to preclude or at least minimize recontamination by airborne

particles, aerosols or direct contact transfer. When finally installed the optical housing should not shed particles from fasteners or seals and should not outgas, which could cause an undesirable film to condense on the optical element.

This paper discusses many of the techniques currently being used for cleaning optics and several new methods under investigation. It also discusses clean room procedures for reducing recontamination after cleaning.

W. J. Comfort, III and C. T. Crowe, *Dependence of Shock Characteristics on Droplet Size in Supersonic Two-Phase Mixtures*, Lawrence Livermore Laboratory, UCRL-80748 (1978). Submitted to Proc. Symp. on Polyphase Flow in Turbomachinery, ASME Winter Annual Meeting, San Francisco, CA, December 10-15, 1978.

In a dispersed two-phase flow, the mixture chokes at a velocity well below the vapor choking velocity, as shown by the velocity at the throat of a converging-diverging, two-phase, supersonic nozzle. The formation and abruptness of a normal shock wave in a two-phase mixture depends strongly on the coupling between phases, particularly upon droplet size. As droplet size becomes small, the mixture behaves as a continuum, and sharp discontinuities can occur at velocities above the two-phase choking velocity but below the vapor sonic velocity. An approximate analysis is performed to indicate the droplet size at which continuum behavior might be expected to occur. A numerical model, which includes the drag, buoyancy, Basset force, and the force associated with the virtual mass effect, is used to show droplet-size dependence in two-phase normal shock waves. For the examples presented, continuum behavior apparently is approached at droplet diameters between 1 and 2 μm , even through normal shock waves.

W. J. Comfort, III, *Modeling the Performance of a Two-Phase Turbine Using Numerical Methods and the Results of Nozzle, Static Cascade, and Windage Experiments*, Lawrence Livermore Laboratory, UCRL-80749 (1978). Presented at Symp. Polyphase Flow in Turbomachinery, ASME Winter Annual Meeting, San Francisco, CA, December 10-15, 1978.

Performance models for a two-phase turbine were developed to verify our understanding of the loss mechanism and to extrapolate from the single-nozzle test condition to a full-admission turbine. The numerical models for predicting the performance of the nozzle and the combined nozzle and

rotor are described. Results from two-phase, static cascade tests and disk-friction and windage experiments are used to calibrate the performance model(s). Model predictions are compared with single-nozzle prototype-turbine test results, and extrapolations are made to a full-admission design. The modeling also provides predictions of performance for turbines with various blade geometries, inlet conditions, and droplet sizes. Thus the modeling provides insight into design improvements.

W. J. Comfort, III, *Applicability of the Hero Turbine for Energy Conversion from Low-Quality, Two-Phase, Inlet Fluids*, Lawrence Livermore Laboratory, UCRL-80751 (1978). Submitted to Proc. Symp. on Polyphase Flow in Turbomachinery, ASME Winter Annual Meeting, San Francisco, CA, December 10-15, 1978.

The Hero turbine is frequently said to be particularly suited for two-phase geothermal-energy conversion. Its functional simplicity makes it an obvious candidate for use of a very low-quality steam-water mixture as a working fluid. The performance characteristics for the single-phase expander derived are extended to address two options for handling the two-phase mixture in the Hero turbine. The Hero turbine is found to be best suited to fluids that are single-phase at the entrance to the turbine and to expansions that involve low enthalpy change. The turbine appears well suited to saturated liquid expansion in which the fluid becomes two-phase after entering the turbine.

T. W. Alger, C. T. Crowe, and W. H. Giedt, *A Laser-Doppler Velocimeter for Measuring Droplet Velocities in Two-Phase Liquid-Dominated Nozzle Flows*, Lawrence Livermore Laboratory, UCRL-80790 (1978). Submitted to Symp. Measurements in Polyphase Flows, ASME Winter Annual Meeting, San Francisco, CA, December 10-15, 1978.

A new laser-Doppler velocimeter (LDV) arrangement for measuring droplet velocities in high velocity liquid-dominated two-phase nozzle flows was developed. The transmitting optics arrangement for this LDV system is identical to that of a dual beam heterodyne LDV, i.e., the light beam from a single frequency argon laser is divided into two parallel identical beams, which are focused to an intersection volume in the flow. The light back-scattered from droplets traveling through this volume is collected for analysis using a scanning confocal Fabry-Perot interferometer (FPI). Because of the dual beam arrangement an unscattered

or reference beam is not necessary, and the optical alignment ease and stability are greatly improved over similar LDV-FPI systems. Results of droplet velocity measurements in high velocity, high droplet concentration nozzle jet flows are presented.

J. H. Pitts and E. W. McCauley, *Vent Clearing During a Simulated Loss-of-Coolant Accident in a Mark I Boiling-Water-Reactor Pressure-Suppression System*, Lawrence Livermore Laboratory, UCRL-80873 (1978). Prepared for Proc. European Nuclear Society/American Nuclear Society International Meeting on Nuclear Power Reactor Safety, Brussels, Belgium, October 16-19, 1978.

The authors are studying the response of the pressure-suppression containment system of Mark I boiling-water reactors to a loss-of-coolant accident (LOCA). This response is a design basis for light-water nuclear reactors. Part of the study is being carried out on a 1/5-scale experimental facility that models the pressure-suppression containment system of the Peach Bottom 2 nuclear power plant. The test series reported here focused on the initial or air-cleaning phase of a hypothetical LOCA. Measured forces, measured pressures, and the hydrodynamic phenomena (observed with high-speed cameras) show a logical interrelationship.

R. C. Ling, R. H. Bulmer, T. A. Cutler, J. H. Foote, and J. A. Horvath, *Ion Trajectories of the MFTF Unshielded 80-keV Neutral-Beam Sources*, Lawrence Livermore Laboratory, UCRL-81086 (1978). Presented at CUBE Symposium, Los Alamos Scientific Laboratory, Los Alamos, NM, October 4-6, 1978.

The trajectories of ions from the Magnetic Fusion Test Facility (MFTF) 80-keV neutral-beam sources are calculated to obtain a preliminary understanding of the ion-beam paths and the magnitude of the power densities. This information will be needed for locating and designing thermal (kinetic-energy) absorbers for the ions. The calculations are made by employing a number of previously written computer codes. The TIBRO code is used to calculate the trajectories of the ions in the fringe magnetic field of the MFTF machine, which can operate with a center-field intensity of up to 2 T. The SAMPP code gives three-dimensional views of the ion beams for better visualization of the ion-beam paths. Also used are the codes MIG, XPICK, and MERGE, which were all previously written for manipulating data.

S. C. Cowin and L. E. Trent, *Force of Extraction for a Cylinder Buried in Sand*, Lawrence Livermore Laboratory, UCRL-81182 (1978). Submitted to *International J. Mechanical Sciences*.

Lower bounds are derived for the force needed to extract a cylinder from a larger cylinder when the annular region between the two cylinders contains a granular material. Some aspects of the method of solution are new and can be applied to many similar problems.

B. J. McKinley, *Ultrasonic Imaging*, Lawrence Livermore Laboratory, UCRL-81194 (1978). Submitted to First International Symp. Ultrasonic Materials Characterization, National Bureau of Standards, Gaithersburg, MD, June 7-8, 1978.

See article in this quarterly for details.

T. H. Bater, R. E. Patrick, and W. R. Call, *A Neutral Beam Line Pump with Helium Cryotapping Capability*, Lawrence Livermore Laboratory, UCRL-81196 (1978). Prepared for the 10th Symp. Fusion Technology, 1978, Instituto di Elettronica ed Elettrotecnica Via Grandenigo, 6/a I-35100 Padova, Italy, September 4-8, 1978.

A neutral beamline cryopump has been developed that will cryocondense hydrogen and cryotrap helium either separately or simultaneously. The pump will be part of the apparatus for a direct conversion experiment to be installed on the LBL neutral beam test stand. The location of the pump between the direct converter electrodes and the neutral beam dump will maintain a sufficiently low pressure for efficient collection of the energetic beam ions. Further, the helium cryotrapping capability will permit the use of helium beams with the advantage of a single ion species in direct converter development.

The specific pumping speed for hydrogen is 10.5 liters/sec/cm² at 6×10^{-5} torr. The maximum specific pumping speed for helium (cryotrapped at an argon to helium flow ratio of 30:1) is 3.52 liters/sec/cm² at 8×10^{-6} torr. The area of the chevron baffle is 1.5 m² providing a maximum through put of 16 torr-liters/sec of hydrogen and 4 torr-liters/sec for helium both at 1×10^{-4} torr.

The design and development details and the operational characteristics will be discussed.

B. W. Maxfield, *Ultrasonic Measurements of Thin Metallic Interfacial Regions*, Lawrence Livermore Laboratory, UCRL-81201 (1978). Submitted to First

International Symp. Ultrasonic Materials Characterization, National Bureau of Standards, Gaithersburg, MD, June 7-9, 1978.

A typical braze joint consists of a metallic region which wets the surface of the two metals being joined, thereby achieving a bond of good mechanical integrity. An ultrasonic signal reflected from this bond can normally distinguish between bonded and unbonded regions but gives little information about the strength of such a region. For some brazes (and other bonding operations), there is a good correlation between thickness and bond strength in that a bond falling within a specified thickness range can be shown to perform adequately while both thinner and thicker bonds exhibit degraded performance. For a 50 μ m thick braze, ultrasonic reflections are "separated" by roughly 16 nsec. For any real transducer, this means that there is significant overlap of the front and back surface reflections. We have studied a model system consisting of thin (12 to 90 μ m) aluminum bonded to the back surface beryllium. By computer fitting the time dependence of the elastic disturbance reflected from the beryllium-aluminum region to a two-plane wave reflector model and allowing for multiple reflection, we correctly predict the interface separations. Details of the data acquisition and analysis, including the fitting procedure and an error analysis, are given.

Accuracy depends upon the separation; a 50 μ m thick (2 mil) bond can be determined with an accuracy of about 20%. The thickness of highly graded joins, consisting of two different braze materials, can be determined with an accuracy of about 30%.

R. H. Toland and M. W. Schwartz, *Composite Materials in Automotive Energy Storage Systems*, Lawrence Livermore Laboratory, UCRL-81239 (1978). Prepared for Proc. ASME Symp. Composite Materials in the Automotive Industry, ASME Winter Annual Meeting, San Francisco, CA, December 13-14, 1978.

Energy storage is essential to the future energy plans of the U.S. Load leveling, power boost, and energy recovery can be accomplished by energy storage systems to improve the efficiencies of power generation and power supply as well as the effectiveness of intermittent power generators. Two storage systems that are applicable to transportation and can benefit by the use of composite materials are (1) compressed air storage (CAS), and (2) flywheel energy storage (FES). The CAS system can use a

composite pressure vessel with load-sharing metal liner whereas the FES system can use a composite flywheel rotor. The potential of these materials is seen in the design performance index where a direct relationship exists between the energy density and the specific strength of the composite material. This relationship, in addition to the potential of low cost and the less traumatic failure modes of fiber composite materials, has stimulated composite flywheel rotor development.

J. W. Gerich, *An Inflated Cylindrical Solar Concentrator*, Lawrence Livermore Laboratory, UCRL-81250 (1978). Prepared for 1978 Annual Meeting of the American Section of the International Solar Energy Society, August 28-31, 1978.

We are developing a concentrating solar collector to produce pressurized hot water up to a temperature of 170°C. The collector structure consists mainly of an inflated thin-film plastic cylinder that is clear on the upper portion and is an aluminized reflector on the lower portion. The reflector concentrates sunlight on a receiver tube which is jacketed with a heat transfer suppressing, thin-film plastic cylinder. Because of its simplicity and large size, we believe this collector will be able to produce steam competitively with that produced by fossil fuels such as oil.

We have written computer codes to analyze the optical and thermal properties of this collector. Results indicate that weekly tilting of the collector provides over 90% of the energy available from continuous tracking. Combining calculated optical and thermal efficiencies gives an overall collector efficiency of 20% for 170°C operation. Our first experimental collectors are 8m long with an outer diameter of 1m.

R. L. Wood and E. A. Platt, *Shallow Solar Pond Powered Irrigation Pumping - A Feasibility Study*, Lawrence Livermore Laboratory, UCRL-81251 (1978). Prepared for 1978 Annual Meeting of the American Section of the International Solar Energy Society, Denver, CO, August 28-31, 1978.

An irrigation pumping system using an organic fluid Rankine cycle engine "fired" by shallow solar ponds (SSP) is studied. A 150 kW system (125 kW deliverable for pumping) is specified. Component selection and sizing was done so as to maximize the amount of irrigation water pumped, from April 1 through October 31, per dollar invested.

The performance and cost projections for a SSP irrigation pumping system at a nominal 150 kW

capacity indicate that such a system is not competitive with diesel power or purchased electrical power for irrigation purposes. However, it may still be less expensive per unit work output than the currently DOE funded irrigation pumping systems using relatively more costly concentrating collectors.

R. A. McWilliams, *Modified Diamond Dies for Laser Applications*, Lawrence Livermore Laboratory, UCRL-81269 (1978). Prepared for 48th Annual Convention, Wire Association International, St. Louis, MO, October 15-19, 1978.

We are using a modified wire drawing die for spatial filtering techniques. It was designed for use in high power laser systems.

The diamond aperture is capable of enduring high intensity laser frequency without damaging the laser beam profile. The diamond is mounted at the beam focus in a vacuum of 1×10^{-5} Torr. The vacuum prevents plasma forming at the diamond aperture, thus enabling the beam to pass through without damaging the holder or aperture.

The spatial filters are fitted with a manipulator that has three electronic stepping motors, can position the aperture in three orthogonal directions, and is capable of 3.2 μm resolution.

Shiva laser system is using 105 diamond apertures for shaping the High Energy Laser Beam.

J. O. Hallquist, *A Numerical Treatment of Sliding Interfaces and Impact*, Lawrence Livermore Laboratory, UCRL-81305 (1978). Prepared for 1978 ASME Winter Annual Meeting, San Francisco, CA, December 10-15, 1978.

Details of a numerical procedure are described for handling sliding interfaces and impact in large deformation explicit finite element and finite difference codes that use four node constant stress quadrilateral zones in the spatial discretization. The method is applicable to problems in solid mechanics and hydrodynamics. An example calculation is provided that shows a practical application of the method.

B. J. McKinley, *Ultrasonic Imaging Project and Test Bed*, Lawrence Livermore Laboratory, UCRL-81338 (1978). Prepared for Proc. ARPA/AFML Review of Progress in Quantitative NDE, Scripps Institution of Oceanography, LaJolla, CA, July 18-21, 1978.

See related article in this quarterly for details.

P. C. Baker and N. J. Brown, *Polishing Single-Point Diamond-Turned Metal Reflective Optics*, Lawrence Livermore Laboratory, UCRL-81368 (1978). Prepared for *Optical Engineering Review*.

A procedure is described for the use of diamond impregnated pitch and silicon oil which has produced surfaces which appear to be as smooth as 5 Angstrom rms on small flat samples removing the objectionable diffraction producing grooves that sometimes accompany diamond turning. Possible mechanisms are described together with the procedures and equipment used to polish an x-ray microscope and a UV telescope.

M. A. Hoffman, *Convective Cooling of Grids in Continuously Operated Neutral Beam Injectors*, Lawrence Livermore Laboratory, UCRL-81570 (1978). Prepared for *Nuclear Technology*.

A systematic method for determining the heat flux limits of convectively cooled grids of varying lengths for future, continuously-operated neutral beam injectors is presented. The many important constraints which impose limits on the heat flux capability of such grids are discussed and numerical results are presented for one illustrative example of helium-cooled TZM grids. The results indicate that for the shorter grid lengths, the heat flux is limited by either sputtering or material stresses, for intermediate grid lengths by sputtering and for longer grid lengths by accelerator optics considerations.

RAC