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Mechanical Engineering Department

Technical Review

Scientific Editor: W. B. Simecka
General Editors: R. A. Condouris
C. Talaber

MASTER

January 1, 1980

Lawrence
Livermore
Laboratory

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NUCLEAR TEST ENGINEERING DIVISION

The Nuclear Test Engineering Division (NTED) provides mechanical engineering and technical expertise for preparing and fielding nuclear tests and for conducting both analytical and experimental studies for the U.S. Nuclear Regulatory Commission that involve nuclear safety in general and seismic response of reactors in particular.

Nuclear Testing

Our nuclear testing activities and responsibilities involve the design, structural evaluation, fabrication, and proof testing of device canisters that position and protect nuclear explosives in an underground environment. We synthesize, procure, and certify the arming and firing systems and are responsible for the necessary bunkers, cables, and the interface with the control room. At the ground zero site, we enforce appropriate controls over the nuclear explosive and firing system to comply with the Department of Energy safety rules. The necessary underground diagnostic system is provided by us, and it requires development and fielding of mechanical equipment and the designing of downhole emplacement systems. We have the task of developing containment systems that meet zero-detectable radioactivity release requirements. In addition, we are working toward advancing the containment technology by improving the material and hardware. This involves carrying out ground shock analyses, thermal fluid investigations, gas flow studies, and structural analyses. Our special or advanced development projects include the development of new diagnostic techniques, optimizing field engineering concepts, new stemming plans and procedures, and development of appropriate design and analysis methods.

Reimbursable Programs for the U.S. NRC

The safety of nuclear power plants and associated facilities is the major concern of the Nuclear Regulatory Commission (NRC). Over the past 6 years, we have been involved with more than 40 separate NRC reimbursable contracts concerning more than 30 technical areas. Most of the facilities of the nuclear fuel cycle have been addressed in our work from the structural integrity viewpoint including fuel processing and fabrication, power generation (particularly containment sys-

tems), interim waste storage, and spent fuel reprocessing. Our work can be grouped into three categories: seismic engineering, applied mechanics, and systems engineering and risk estimation. In seismic engineering, we develop analytical techniques, establish design criteria, and design requirements, carry out dynamic structural analyses, assess the seismic hazard at a specific site, and quantify the conservatism in the design of nuclear power plants. A general goal we have is to establish LLL as a national and international center of seismic excellence. Our applied mechanics activities include fluid-structure interaction studies, large-scale pressure suppression safety experiments, transportation of hazardous materials investigation, and missile impact effects studies. Our work in systems engineering and risk estimation involves seismic trip studies, materials control, waste management, and reactor safety.

(For further information, contact Richard J. Wasley, Ext. 29966.)

Seismic Design Criteria Evaluated for NRC

How conservative are the seismic design criteria for structures? Can we reduce these conservatisms? (Conservatisms are the allowances in a design for the uncertainties or unknowns in each step of the design.)

To help answer these questions, the Nuclear Regulatory Commission (NRC) initiated the Task Action Plan A-40 (TAP A-40) program. This high priority program is to identify and quantify the conservatisms inherent in the seismic design sequence in current NRC criteria.

The program is intended to provide a short-term improvement of these criteria until long-term solutions are obtained from the Seismic Safety Margins Research Program (SSMRP) currently underway here under the direction of Paul Smith and Frank Tokarz.

The TAP A-40 program consists of ten tasks, each of which will investigate and analyze a particular area of the NRC seismic design criteria chain. Included in these tasks are investigations of the conservatisms inherent in the following:

- Regulatory guide 1.60 spectra.
- Regulatory guide 1.60 time histories.
- Damping.
- Soil-structure interaction.
- Broadening of spectral peaks.
- Nonlinear structural response.
- Subsystem response.
- Site-specific response spectra.

About half of the tasks were done by or under the direction of members of NTED. These include:

- Task 1—quantification of seismic conservatism.
- Task 2—elastic-plastic seismic analysis. (See article in ME Quarterly report UCRL-50016-79-1.)
- Task 3—site-specific response spectra.
- Task 8—development of strong motion near-field data.
- Task 9—development of seismic energy attenuation functionals.
- Task 10—review and implementation.

Provide Technical Review and Recommendations

Task 10 is to provide a technical review of the results of the other tasks and to recommend changes to the existing NRC seismic design criteria. To accomplish this objective and to provide the best technical product possible, we adopted a team approach. The team consisted of a core group of LLL personnel, NRC staff members, and consultants from the academic and engineering communities.

We divided the areas of review into four categories:

- Ground motion.
- Soil-structure interaction.
- Structures.
- Equipment and components.

The team has reviewed the results of the TAP A-40 tasks, assessed the current techniques of seismic design and analysis in these four areas, and made recommendations for changes to current

NRC criteria. These changes are intended to bring the NRC seismic design criteria in line with the current state of the art. These recommendations include:

- Changes in the specification and application of ground motion input for the design of structures and equipment.

- Significant changes to the philosophy and specifications for soil-structure interaction analysis.

More specific guidelines for the seismic design and analysis of special structures (i.e., buried pipes, conduits, and above-ground vertical tanks).

- Specific criteria for the modal response combination of high frequency modes.

- The allowance of limited amounts of inelastic energy absorption capability for typical category I structures.

- Revision of damping values for design based on the type and condition of the structure and the stress levels of interest.

- Direct generation of floor spectra for equipment design.

- Accounting for uncertainties in the generation of floor spectra through multiple analyses with variation of parameters and through the use of non-exceedance probabilistic generation of floor spectra.

- The option of using multiple time histories (real and synthetic), randomly selected, when the time-history approach is used.

- Reduction in the number of operational basis earthquake cycles required, for design consideration, during the plant life.

These recommendations reflect the increased understanding in the art of seismic design as well as the relative degree of uncertainty that still exists in the various areas of the seismic design sequence. However, much additional research needs to be done. Programs such as the SSMRP will expand upon and investigate in greater detail the conservatism studied under the TAP A-40 program.

(For further information, contact David W. Coats, Jr., Ext. 20107.)

NUCLEAR EXPLOSIVES ENGINEERING DIVISION

Our major mission is to support the Laboratory's Nuclear Explosives Program (NEP) in developing operational nuclear weapons systems for the U.S. stockpile. We also support the Non-nuclear Ordnance Program, Organic Materials Division, and H (Physics) Division. We perform studies and hardware development for Y-Program, Nuclear Regulatory Commission (NRC), Z-Division, and the Defense Nuclear Agency (DNA).

NEED's project teams are dedicated to specific engineering areas: conceptual nuclear design, strategic systems, development and production/liaison for nuclear weapons systems, advanced fission and fusion systems, hydrodiagnostics development, and maintenance and upgrade of the Site 300 test facilities. Our Applied Mechanics Group supports Laboratory programs with calculational expertise in solid mechanics and transport phenomena, and the Auxiliary Systems Group supports Laboratory programs with expertise in high-pressure gas-technology.

(For further information, contact Ronald B. Carr, Ext. 28301.)

Thermomechanical Modeling of the Welding Process

One of the most important design and fabrication considerations in the mechanical design of nuclear weapons is the welding and brazing of components. The distortion of welded components must be held to a minimum in order to assure that the resultant geometries will satisfy the stringent physics requirements. In addition to minimizing distortion, the strength of the weld is extremely important. This is particularly true in pressure vessels and weapons seeing harsh thermal and dynamic environments, such as the artillery fired atomic projectiles (AFAPs), lay-down bombs, and re-entry strategic weapons. Future weapons will demand even greater strength and precision than current technology provides.

Objectives of Research

We are developing and refining the methodology for two-dimensional analysis of the state of

temperature, stress, and deformation in welds. The analysis methodology will account for temperature-dependent thermal and mechanical properties of the material, including plasticity. (This research is funded by the Mechanical Engineering Research Program.)

Initially, research is intended to evaluate experimentally an existing capability to model nonlinear heat transfer and thermoplasticity by means of our finite-element codes. The long-term goal is to refine and develop the constitutive models and algorithms necessary to characterize the thermomechanical response of welded structures. In doing so, we will have a reliable methodology for the prediction of weld distortions and stresses and resultant heat-affected zones.

At present, the development of a weld for a given component is iterative in nature and very costly. Usually extensive weld parameter studies are required to optimize strength and minimize distortion. It is common to spend tens of thousands of dollars on the development of a single weld design and procedure. Eventually a reliable predictive capability will be developed that will allow the design teams to *a priori* determine the state of residual stress and deformation for a given weld geometry and procedure (to within an acceptable degree of accuracy) and will reduce the number of iterations in the weld development cycle and therefore the costs.

The nuclear design teams currently make extensive use of analysis codes in order to analyze the state of stress and deformation in components when subjected to the stockpile to target sequence (STS) environments. However, a given structural component is usually assumed to be stress free, and therefore, the effects of residual stresses due to welding are neglected. There are numerous examples in nuclear design when these effects should not be neglected, particularly when low ductility materials such as beryllium are under consideration.

Gas-Tungsten-Arc Welding Selected

During the past year, our Mechanical Engineering Research Program was devoted to understanding the physics of the gas-tungsten-arc (GTA) welding process, developing an experimental program, and modeling the thermal and mechanical aspects of the problem. The GTA was selected

based on the extensive coverage in the literature and frequent use in weapon and industrial welds. A series of experiments were performed on round nickel plates where a GTA was used to melt partially through the central region. Several experimental techniques were used to provide thermal and mechanical histories including: radiometers, thermocouples, metallography, motion pictures of weld pool solidification, contour measurements, Moiré fringe patterns, and displacement gages. More refined Moiré techniques are being implemented and will be applied in the near future.

An axisymmetric weld was analyzed using the TACO code to provide the nodal thermal history file. This file became the input for the NIKE2D mechanical code. The GTA literature study yielded guidance as to the proper heat flux distribution for the arc model in the thermal code. Numerous aspects of the weld process have been quantified by prior weld researchers. These include weld pool dynamics, arc energy deposition, and temperature effects on mechanical properties. These investigations into the physics of the GTA weld were used to

rationalize the assumptions required for the modeling process.

Encouraging Results

Comparison of analytical and experimental results is very encouraging. The predicted motion of the liquid-solid interface during solidification and the location determined from motion pictures were virtually identical. Thermocouple measurements and corresponding nodal temperature histories were also in close agreement (Figs. 1 and 2).

The Moiré data is still being reduced, but initial indications show a similar pattern of radial strains to the analytical predictions. The most significant result of this year's effort is the excellent correspondence between the measured and predicted plate contour, both during the weld and in the residual state (Fig. 3).

Future Plans

For the coming year, we will continue to concentrate on the two-dimensional welding experiments and the corresponding analysis of those experiments. In particular, we will concentrate on five

FIG. 1. Schematic of the welding experiment.

FIG. 2. Experimental and calculated temperature histories for three points on the Ni plate.

- tasks that will help to explain the physics of the welding process:
- Energy flux distribution in the arc.
 - Measurement of the solid-liquid heat transfer coefficient.
 - Refinement of experimental measurements.
 - Improvement of the thermoplasticity model.
 - Additional two-dimensional plate experiments.

(For further information, contact David B. Duncan, Ext. 28463.)

Note: Dashed curves are experiment and solid curves are calculation.

(a) Radial displacement of the solid-liquid interface during solidification.

(b) Residual contour of the lower side of the Ni plate.

FIG. 3. Correspondence between the measured and predicted plate contour was excellent, both during the weld and in the residual state.

Calculations of an Optimum Shape Charge for Non-nuclear Submunition

The forward charge on a non-nuclear submunition softens a path in concrete targets so that the follow-through charge can penetrate before detonating. We have tested both copper and aluminum shape charges with various cone angles and liner thicknesses and self-forging fragment (called Miznay-Schardin) devices against concrete targets. For our purposes, the best results thus far have been obtained from a 4% thick, 105° aluminum cone-shaped charge. (Percent indicates the ratio of liner thickness to high explosive diameter.)

Using the DYNA2D computer code, we have made calculations of various forward-charge liner geometries to obtain information on jet velocity, shape, and kinetic energy. Figure 4 shows a time-sequence of the formation of a 4% thick, 105° aluminum liner. The calculated rigid-body velocity at 25 μ s is 0.35 cm/ μ s. The dotted line indicates the original position of the aluminum liner. Severe jetting along the centerline of the shaped charge liner distorts the Lagrangian grid and stops the calculations shortly after this time. However, at 25 μ s, the liner has received most of its energy from the high explosive, and although the jet is still stretching, the rigid body kinetic energy has reached its maximum failure. Figure 5(a) is a plot of axial velocities of the tip, tail, center, and wings illustrating the velocity gradient that continues to stretch out the jet. At 25 μ s, the wing tips are moving radially inward at 0.1 cm/ μ s.

A plot of calculated rigid-body kinetic energy in the forward direction versus charge-to-mass ratio is shown in Fig. 5(b) for various liner thicknesses at 105° cone angle. The peak in kinetic energy coincides roughly with the experiment that produced the maximum effective crater volume. Experiments on liners of 2, 4, 6 and 8% showed a maximum crater volume at 4% compared to the peak in kinetic energy at 5%. Calculations shown in Fig. 5(c) for a 4% liner thickness with cone angle varying between 100 and 120°, show very little difference in kinetic energy for different cone angles. This result agrees with experimental damage results.

Additional calculations show a 13% increase in kinetic energy results from changing the case from aluminum to steel. Peripheral initiation also in-

FIG. 4. Calculated time sequence of the formation of the shape charge liner.

FIG. 5. Computed results for the shape charge design (HE mass/liner mass = c/m).

creases the high explosive efficiency, but requires certain design changes.

(For further information, contact Dean B. Tuft, Ext. 28776.)

PELE-IC: Computer Code Calculates Loads and Structural Responses

The PELE-IC computer code couples an incompressible Eulerian fluid algorithm to a Lagrangian finite-element shell module. The application is containment analysis of pressure suppression in boiling-water reactors. The computer program calculates loads and structural response from air blowdown and the oscillatory condensation of steam bubbles in a water pool. The fluid, structure, and coupling algorithms are verified by calculation of solved problems from the literature and from blowdown experiments. Only one of these verifications is discussed below.

Vibration of a Submerged Cylinder

Verification of the coupling algorithm¹ between a Eulerian incompressible fluid mesh and a Lagrangian shell module was tested for the case of a submerged cylindrical shell surrounded by an an-

nular liquid region. The inextensible elliptical bending mode ($n = 2$) was excited, and the resulting frequency of the structure-fluid system was compared to the exact result.² The system, whose dimensions (shown in Fig. 6) were chosen to conform to calculations by Schroeder and Marcus³ and

FIG. 6. Geometry for submerged cylindrical shell.

Nickell and Dunham,⁴ was excited by the use of nodal forces applied to the shell to push inward at the minor axis and pull outward at the major axis. We chose these forces to be equal and temporally ramped for the first 2 ms of the transient. The 90° segment formed by the intersection of the elliptical axes was composed of an 80-by-80 Eulerian fluid mesh and eight shell finite elements.

Figure 7 shows a computed two-dimensional flow field, which reverses direction in each cycle. The computed, normalized fluid velocity fields along the elliptical axes are compared to the exact profile² in Fig. 8 where the computed velocity distributions are observed to approach the exact, quasi-steady distribution long after the initial excitation has been removed. In Fig. 9, the amplitude of the computed nodal shell response at either elliptical axis is observed to approach an asymptotic limit long after the initial excitation is terminated, this being a result of readjustments in the potential energy of the shell to supply sufficient kinetic energy to the massive quantity of liquid as the latter approaches the quasi-steady velocity profile (Fig. 8). The frequency observed from the computed results of Fig. 9 is 37 Hz, which compares closely with the exact incompressible frequency of 37.7 Hz. At this frequency, the associated wavelength within the fluid is large (about 1300 cm) compared to the largest dimension of the system (82.6 cm); conse-

FIG. 7. Sample computed flow field at 20 ms. (Velocity vectors are shown in vicinity of shell.)

FIG. 8. Radial velocity profiles along elliptical axes.

FIG. 9. Shell nodal response at elliptical axes.

quently, the incompressible assumption for the liquid is appropriate.

The advantage of treating the fluid in an Eulerian coordinate system is seen by our success in accommodating large relative tangential motions between shell and fluid (in the $n = 2$ mode, the two tangential motions are always opposed). Such cases have escaped previous solution owing to numerical problems when the finite-element method is applied to the relatively large tangential motion between fluid and structure. These problems are discussed in a survey paper by Nickell and Carey.⁵

(For further information, contact Charles S. Landram, Ext. 28569.)

High-Speed Camera and Optical Support Facility Consolidated

We have consolidated the high-speed camera facility and optical support for Site 300 into building 814. The building layout is ideal for its new function. There are eight usable rooms, a restroom, and a building equipment room. Utilities include air conditioning, lighting, water, house air pressure, and a helium and nitrogen trailer. All of the rooms, except for one (the office), are windowless, which is desirable for optical work. Each room is tailored for a specific function.

Room 101, formerly an explosive test cell surrounded by 20.3-cm-thick concrete walls, will be used as an unmanned area for camera runup. In addition, this room will be used for rotor destruct tests for improving rotor reliability and general designs.

Other rooms will house grinding and cutting optical components; an operations room that will house the rotor speed control system and a replica of the bunker electronic firedown system; small light-machine shop; a combined dark room and optical component polishing room, and the office with a Tektronix 4051 microprocessor. The operations room will be used for our rotor checkout testing by

dynamically checking the rotors at maximum speed on the turbine test stand cell (Fig. 10).

We will use the largest room (10.7 by 6.1 m) for the following:

- Acceptance inspection on new and repaired rotors by recording the turbine mirror interferogram.
- Modification of high-speed cameras and rotors.
- Rebuilding cameras that have had rotor failures in Fig. 11.
- Realigning and checking the optical systems of the cameras.
- Storing optical components.

Essentially, this is an optical laboratory complete with lens benches, vibration-free optical table, interferometers, and an optical comparator and monochromatic lights. It is also a repair shop and an optical component storeroom.

Our work involves 25 high-speed framing cameras, 28 high-speed streaking cameras, and 72 high-speed mirror turbines.

(For further information, contact Gary Y. Otani, Ext. 112260.)

(a) Turbine test stand and cell

(b) Instrument records the turbine mirror interferogram

FIG. 10. Equipment used in the turbine quality assurance program.

FIG. 11. Damaged model 6 camera before overhaul. Damage occurred as a result of turbine overspeed.

On-Site Testing of Material Configurations with Multiple Shape Charges

We have designed experimental hardware that allows us to simultaneously test five material configurations reacting to miniature shape charges. Testing is performed in a large (2.03-m i.d.) steel tank located in building 225 (Fig. 12). Each of the five shape charges contain 23 g of explosives, which does not exceed the tank limitation of 350 g total high explosives. Diagnostics consist of post-shot penetration measurements and/or flash radiography.

A specially designed film cassette holds two 35.6-by-43.2-cm films to form a 44.2-by-71.1-cm film plane. This film cassette is placed on a prepositioned stand so the film plane can be easily relocated during film changes. To prevent shrapnel penetration of the film cassette, the shape charges are located in 10.2-cm o.d. steel tubing of 6.35-mm wall thickness, 10.2 cm long. The steel tubes contain low density rigid foam with a through center hole to provide shape charge standoff from the steel tube.

Flash x-ray heads are located in two vertically stacked specially designed flanges attached to tank

ports. The flanges are separated by 1.14 m and the heads angled to direct their center lines to a common point. Shadow boards are located inside the tank at each flange to screen unwanted radiation from the film plane. With this configuration, a 15.24-cm-wide object plane can be radiographed at four different times by double exposing the film. The shot holder (and target position) may be located at various positions relative to the 15.2-cm object window. To prevent tank penetration from the shape charge, a backstop of steel plates is located on a stand behind the targets. By adjusting the stack array, the plates are repositioned for use with more than one shot for cost effectiveness. The stack thickness exposed to the shot is 20.32 cm minimum. Jet penetration is 15.2 cm at optimum standoff.

We attained the design goal of maximum reuse of test hardware with ease of repeatedly setting similar tests. The steel shape charge holders and the rigid foam shot and target holders are destroyed. The film cassette and other stands have survived about 85 shape charges to date.

(For further information, contact Jack Rego, Jr., Ext. 28873.)

(a) Five shape charges and steel tank.

(b) Shape charge test configuration as viewed from "x"-ray head.

FIG. 12. Special steel tank in building 222 for testing material configurations reacting to miniature shape charges.

Constitutive Modeling of HE Materials Will Predict Response of Weapon Structures

Constitutive models that we developed for high explosive (HE) materials will be used to predict the response of weapon structures using HE as a load-carrying component. In particular, we are studying two classes of material models for use in different time response regimes and are performing experiments that will show how well each model represents the constitutive behavior of the HE.

The first model, which is used in a rapid loading environment such as in AFAPS (Artillery Fired Atomic Projectiles) and laydown weapons, is of the elastic-viscoplastic type and will use a series of moderate strain rate, confined and unconfined compression tests.

In the confined compression test shown in Fig. 13, the thickness of the confining sleeve is varied in order to control the degree of confinement. A displacement time history is imposed on the specimen in order to induce strain rates up to 1.0 s^{-1} . Hoop and axial strain gages on the steel sleeve allow us to deduce the radial stress and strain in the sleeve, and therefore the HE specimen, from simple elastic theory. Thus, the complete time history of stress and strain in the HE specimen is known for varying degrees of confinement and strain rate. From these data, we will be able to improve the constitutive models for high explosives.

In Fig. 14, three experimental stress-strain curves for unconfined LX-10-1 HE are shown for three different strain rates. As can be seen, the increased strain rate has the net effect of increasing the apparent stiffness of the material.

The second model is a nonlinear viscoelastic model and will be used for long duration loading where creep is important. This model requires a series of constant stress creep and recovery experiments to determine the necessary material functions. The nonlinear viscoelastic stress-strain relation can be derived from the thermodynamic principles and has the form

$$\epsilon(t) = g_0 J(0) \sigma(t) + g_1 \int_0^t \Delta J(\phi - \phi') \frac{dg_2 \sigma(\tau)}{d\tau} d\tau,$$

FIG. 13. Fixture for the confined compression test.

where

$$\phi - \phi' = \int_{\tau}^t \frac{dt'}{a_{\sigma}}.$$

$J(0)$ and $J(t)$ are, respectively, the initial and transient components of the linear creep compliance, and g_0 , g_1 , g_2 , and a_{σ} are the nonlinear stress-dependent material properties. When the stress is sufficiently small, the nonlinear viscoelastic behavior reduces to linear viscoelastic behavior and $g_0 = g_1 = g_2 = a_{\sigma} = 1$. The linear creep compliance is assumed to obey a power law in time, that is,

$$J(t) = ct^n.$$

FIG. 14. Stress-strain curves for unconfined LX-10-1 at three strain rates.

When the stress is sufficiently large, the HE material exhibits nonlinear viscoelastic behavior; a graphical shifting procedure is used for data analysis to evaluate all nonlinear material properties.

We have also obtained the preliminary test data for determining the mechanical properties of a high explosive under uniaxial compression. The creep recovery curves for various loads are shown in Fig. 15(a). The constants $J(0)$, c , and n are equal to 8.084×10^{-6} , 7.889×10^{-6} , and 0.35, respectively.

The stress-dependent material constants a_0 , E_0 , g_1 , and g_2 are shown in Figs. 15(b) and 15(c). The assumptions used in these preliminary data reductions are that the loading and unloading are instantaneous and that the high explosive behaves linearly at the lowest load.

(For further information, contact Roger W. Werne, Ext. 28847.)

(a) Creep-recovery curves for 90503 mock HE

(b) Time scale factor, a_σ .

(c) Nonlinear material properties, g_0, g_1, g_2 .

FIG. 15. Experimental data for the nonlinear viscoelastic model.

NIKE2D and DYNA2D Codes Available on Cray-1 Computer

The static and dynamic, implicit finite-element computer program, NIKE2D, and the explicit finite-difference/finite-element computer program, DYNA2D, are available for general use on the Cray-1 computer. NIKE2D is widely used by engineers in NEED and WED to analyze the structural designs of new weapon systems. Recently, NTED made extensive use of NIKE2D in the analysis of several problems posed by the Nuclear Regulatory Commission. Typical DYNA2D applications include the response of weapon systems

to short duration loadings, conventional ordnance design, and equation-of-state studies.

With no vectorization except that performed by the Cray FORTRAN (CFT) compiler, these programs are twice as fast as their CDC 7600 counterparts. More impressive, however, is the increase in capacity that now approaches 30 000 elements in each code. Postprocessing such large data bases has motivated the development of a new postprocessor called THOR, which is available on Cray-1 and on the CDC 7600s.

The largest calculation to date on the Cray-1 is the simulation of the large scale gap test by John Walton in Chemistry. The calculational mesh for

FIG. 16. Simulation of a large scale gap test by the DYNA2D code.

DYNA2D has nearly 10 000 zones and two-way slide-lines. The large scale gap test provides a measure of high explosives sensitivity. Figure 16 shows a calculated deformed shape of the large scale gap test at 20 μ s. The calculation was continued to 24 μ s—further than was necessary to obtain the desired data.

(For further information, contact John O. Hallquist, Ext. 28756.)

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WEAPONS ENGINEERING DIVISION

Weapons Engineering Division (WED) is responsible for the full range of engineering activities related to nuclear weapons development, production, and maintenance of a major portion of the national stockpile. Additionally, we are facing new challenges in the areas of safety, weapon control, and guaranteed weapon life extension. Our activities require active interactions with the DOD and many DOE agencies such as Sandia Laboratories, Los Alamos Scientific Laboratory, Albuquerque Operations Office, and seven DOE-integrated contractors.

We maintain a variety of activities to fulfill our mission. The development area includes groups involved in new weapon development, environmental testing, weapons control and enhanced safety, initiation systems development, and engineering technology. Production work involves the communication of product definition and design intent to the DOE contractors responsible for component fabrication and assembly, plus an active monitoring of the entire production process. Maintenance of the stockpile requires a large effort in disassembly surveillance of stockpile weapons to assure that design requirements have indeed been met and to monitor physical changes that may eventually limit the useful life of a weapon.

Nuclear weapons are required to withstand rigorous thermal and structural environments, and they must have long reliable lifetimes with essentially no corrective maintenance. Weapons typically utilize combinations of materials that are not normally encountered in more conventional engineering endeavors. These materials are often chemically reactive, they frequently have wide differences in thermal expansion properties, and many have poor structural properties.

These factors offer challenging design and manufacturing problems that require the mechanical engineering disciplines of design, analysis, and manufacturing as well as materials science and chemistry. Our stockpile laboratory testing programs require innovative approaches to large data base management.

The Special Materials (SM) staff provides technical and administrative coordination of weapons development activities at the DOE-integrated contractors for the Nuclear Explosive Program project and production liaison groups.

The SM members interact with plant management and the technical staff at the integrated-contractor plants. The SM staff also acts for the Laboratory as an administrative and liaison engineering group that contracts for the acquisition of noncommercial materials and services from the DOE-integrated contractors, military agencies and other national laboratories.

(For further information, contact Robert J. Craig, Ext. 28296.)

Improved Temperature Measurements on a Rotating, Water-Cooled Substrate at High Voltage

We have redesigned the hot hollow cathode apparatus to improve the measurement of substrate temperature.¹ The new design allows accurate control of the substrate temperature that is necessary to produce high quality coatings for solid-state bonding.

The equipment currently being used to produce these coatings consists of a hot hollow cathode source (see article in UCRL-50016-79-1) that is used at low power levels to produce silver ions for ion bombardment and at high power levels to evaporate silver at a high rate. During ion bombardment the substrate is at negative potential of about 1 to 3 kV, with spikes to 8 kV. The substrate must be rotated to provide a reasonable coating uniformity and cooled to produce desirable coating properties. Even with water cooling, it is possible for the substrate temperature to exceed 500°C. It is therefore highly desirable to have some means of measuring substrate temperature while ion bombarding and coating.

Several Problems with Using Thermocouples

We faced several problems to make this measurement with thermocouples: Since the part rotates, readout of the thermocouple's output from the rotating part requires slip rings; a vacuum seal must also be provided for the thermocouple leads. During the ion bombardment, the substrate is biased at 2 kV superimposed on the thermocouple

millivolt output, and these voltages must be isolated or separated.

Because of these thermocouple readout problems, we first tried a E² Thermodot, TD-17 radiation pyrometer. However, we found that stray radiant energy overwhelmed the energy emitted by the substrate. This made the radiation pyrometer unacceptable for our purposes.

The new measurement system is installed on an R&D hot hollow cathode coating system (Fig. 1). The coating system uses a 61-cm-diam by 61-cm-high water cooled, split bell jar with side port pumping. Mounted on the centerline of the base plate is a hot hollow cathode source. The rotary substrate holder is mounted on the top plate of the bell jar on an O-ring-sealed slider plate. The shaft for the

FIG. 1. Water-cooled rotating substrate-holder with thermocouples.

rotator is 1.5-in. o.d. stainless steel tube to allow room for the coaxial water passages, many pairs of thermocouple leads, and thermocouple connectors. We used 2-3/4-in. Conflat flanges for all shaft interconnections. Copper gaskets are used inside the vacuum jar, while viton gaskets suffice outside the jar.

The rotary vacuum seal is a Ferrofluidics seal with a 1.5-in. o.d. hollow shaft. We attached the 2-3/4-in. Conflat flanges to both ends. Sandwiched between the rotary seal and the slider plate is an O-ring-sealed ceramic spacer, with nylon fasteners, to provide 4-kV isolation for the rotator assembly.

Attached above the vacuum seal is a LLL-designed water rotator. This allows cooling water to be transmitted inside the tube shaft directly to the substrate holder without interfering with the passage of the thermocouple wires.

Above the water rotator is a 10-circuit Airflight slip ring unit on a 1-1/4-in. hollow shaft with a 2-3/4-in. Conflat flange on each end. On top of the slip ring is a thermocouple feedthrough to exit the thermocouple wires from the water jacket.

The thermocouple measuring junction can be made in several ways. We use 1.6-mm sheath thermocouple material. This consists of a nominal 1.6-mm tube made of 304 stainless steel or Inconel 600. In this tube is a pair of 0.25-mm type-K thermocouple wires, tightly packed with magnesium oxide insulating material. The measuring end can terminate in bare wires, a thermocouple bead, or a sealed grounded junction. One method of making the measuring junction is to intrinsically spot weld the bare thermocouple wires to the substrate. The junction is covered with a thin coating of liquid ceramic to form a seal and prevent shorting of the thermocouple wires. Another method of making the measuring junction is to braze a sealed, grounded junction into the substrate. This creates a sealed system and is the best method from a vacuum standpoint.

The sheathed thermocouple enters the water-filled rotator shaft through a 1.6-mm compression fitting. Inside the water jacket, it terminates in a standard miniature thermocouple connector. The mating connector is attached to an extension wire, which is fed up the inside of the shaft. It passes through the vacuum seal, through the water rotator, through the slip rings, and out the thermocouple feedthrough. The connection inside the water jacket allows fixtures to be changed quickly. Low conduc-

tivity water is used at LLL and does not affect the temperature measurements. If connections in the water prove to be a problem, a continuous piece of sheathed thermocouple could be routed through the water jacket.

The extension wire from the thermocouple feedthrough, is connected to the slip ring terminals. Wires are then run to one of several types of readout devices. The most reliable readout device is a self-powered pyrometer, mounted in a dielectric box to provide high voltage isolation. Better accuracy can be obtained by a battery-powered digital voltmeter. When chart recorded data are desired, a transformer-type voltage isolator can be used. This LLL-designed device includes a digital temperature, and a high voltage protected, linearized chart recorder output.

The temperature measurement technique, currently in use, is an R&D measurement system capable of taking up to nine temperature readings from a rotary, water-cooled substrate at high voltage. This system could be adapted to ion plating, ion milling, sputtering, or other processes using high voltage and water cooling.

(For further information, contact Joseph A. Arluck, Ext. 28733.)

Vibrations Analysis of Complex Shapes Now Possible

Using some simple straightforward testing methods and a new empirical modal analysis routine, we recently analyzed in detail the random vibration response of a large, deep aluminum dome.

The dome is part of a design that has suffered vibration failures of parts that are attached to its surface. We suspected that the failures were related to excessive displacement of the surface. The dome has an unusual shape, two concentrated masses that are connected to other components, and a unique clamped boundary. Since accurate results from computer modeling appeared difficult to achieve, an experimental method was chosen. We designed the experiment to measure deflections of the dome's surface and to determine optimum attachment points.

We subjected the unit to a random vibration environment so that deflections could be measured. The mode shapes were then measured separately to

determine the locations of maximum and minimum motion.

The deflections at the concentrated masses were the primary concern. Unfortunately it is difficult to mount a displacement transducer rigidly enough to measure 10-mil relative displacements over a span of 15 cm in a random vibration environment of 10 to 2000 Hz.

Instead of measuring displacement directly, the concentrated masses were replaced by accelerometers of equal mass. The unit was then clamped to an electrodynamic shaker and subjected to the proper random vibration environment while simulating the actual boundary conditions. Accelerations were measured at the base of the dome as well as at the response points. By comparing the rms acceleration levels at control and response points, the rms level of the relative displacements between any two accelerometers at a given frequency can be easily deduced. This method provides a good estimate of vibration-induced displacement without the requirement of a rigidly referenced transducer. In general, accelerometers are much easier to use in a vibration test than are displacement measuring devices.

Once the displacement levels were known, it was still necessary to determine the deformed shape of the dome so that points of minimum deformation could be identified. To supply this information, the Computer Systems Applications group of MED provided a modal analysis technique available on the transportable data acquisition and control (TDAC) minicomputer system.²

A quarter section of the dome was laid out with a grid of 90 points. An accelerometer was then mounted at one of these grid points and an instrumented hammer was used to tap each of the others. TDAC recorded the magnitudes of the hammer taps and accelerometer responses for each impulse, calculated the shapes of the four dominant modes, and displayed them on a cathode ray tube (CRT).

These simple experiments showed that the attachment points were already located in areas of minimum deflection and that the vibrating dome was not influencing the rest of the system. This result focused attention on other components as the cause of the observed failures.

(For further information, contact Rodney R. Archer, Ext. 28164, and Edwin E. Nesbitt, Ext. 21728.)

Wind Tunnel Built for Studying Effects of Rainout Turbulence

Mechanical Engineering has designed and constructed a wind tunnel in building 222 for Rainout Effects Project experiments by D-Division. This equipment will permit D-Division to verify theoretical work on the effect of turbulence on the attachment of radioactive particles to cloud water droplets.

Weather conditions can have a profound effect on the ground deposition of radioactive nuclear debris released in the atmosphere. Generally a free-air nuclear burst (one for which the fireball does not touch the ground) is considered to be "fallout-free." There is supposed to be no fallout because the debris particles that condense from the vaporized materials in the fireball are too small to fall to the ground—they remain suspended in the atmosphere at stabilization altitudes.

Rainout is a process by which these small particles can be deposited on the ground. It is a two-stage process: In stage 1, the radioactive debris particles attach to cloud water droplets. In stage 2, the contaminated cloud water is swept up by raindrops that fall through the cloud—this is the normal process by which raindrops grow.

The crucial unknown in this chain of events is the rate by which the small radioactive debris particles become attached to cloud water droplets. The wind tunnel described here will be used to study the effects of air turbulence on the attachment process.

System Configuration

The tunnel system consists of the basic tunnel structure shown in Fig. 2 and the gas handling and conditioning equipment located outside of room 1161 in building 222 (Fig. 3). The basic tunnel structure includes the stiling, contraction, test and exit diffuser sections, the turbulence-producing jet plate located in the upstream end of the test section, and the exit plenum tank.

The turbulence wind tunnel is a closed-system designed to circulate either air or nitrogen gas from 0 to 14.2 standard m³/min (10 m/s velocity) through the 15.24-cm-diam cylindrical test section at pressures from 0.5 to 1 atmosphere and temperatures to 24°C. The gas handling and conditioning equipment includes the blower-motor, humidifier, aftercooler, mist eliminators, particulate

FIG. 2. Floor plan of turbulence wind tunnel and gas handling and condition equipment for the rainmont project.

FIG. 3. All of the wind tunnel equipment is inside building 222, except for the gas handling and conditioning equipment located outside as shown here.

filter, dehumidifier, plumbing, and associated instrumentation and controls.

The centrifugal blower is capable of delivering a gas volume of $14.2 \text{ standard m}^3/\text{min}$ at a pressure drop of up to 1.5 atmospheres across the jet plate. We can vary the gas velocity through the test section from 0 to 10 m/s by means of a flow-control valve located in the gas supply line upstream of the tunnel.

Gas temperature in the test section can be established from near 0°C to above the design tem-

perature of 20°C . The spray humidifier, located in the exit plenum tank, and the dehumidifier provide automatic control of humidity in the test section at any desired level ranging from 0 to 70% relative humidity.

Attachment Simulation Technique

We will simulate the attachment of nuclear particles to cloud water droplets by injecting ferrous chloride crystals of about a few microns in diameter

into the gas flow upstream of the tunnel stilling section. Droplets of about 50 μm in diameter containing a water solution of luminol will be injected into the gas stream near the turbulence-producing jet plate located at the upstream end of the test section. We have designed and built the experimental particle and droplet generators here to accomplish the above tasks. Upon capturing a dry ferrous chloride particle, the water/luminol droplet emits a pulse of light at a wavelength of about 4250 $\text{\AA}$. These light pulses are detected and counted by light-sensing photomultiplier tubes and associated instrumentation.

Construction of the wind tunnel is complete, and we have made tests that verify its performance characteristics. The facility has been turned over to D-Division to conduct rainout experiments.

(For further information, contact John W. Pruner, Ext. 24405 or William H. Hubbell, Ext. 29149.)

Precision Die Shearing Developed for Accurate Foil Masks

Weapons Engineering Division and Materials Fabrication Division have jointly developed a precision die-shearing capability that allows the fabrication of unusually accurate foil masks of molybdenum and nickel for use in vapor plating (Fig. 4). We have fabricated about 150 masks whose critical dimensions were held to tolerances of ± 0.0025 mm.

Flying plate detonators under development in WED make use of a vapor-deposited exploding bridge foil whose mass must be very accurately controlled. The bridge foil is deposited on a substrate using a thin foil mask to control position as well as the critical dimensions that influence the mass of the bridge foil. The small size dictates tolerances of ± 0.006 mm and sharp edges to meet uniformity requirements. The masks have been made by a photo-etching process, but the cost of high volume production led us to seek a more economical fabrication process.

Die blanking—the manufacture of a part using a punch and die—would provide a significant cost saving, but it was necessary to improve tolerances significantly that normally result from this method. Our approach was to improve the tolerances and alignment of the die set, the punch, and the die and

FIG. 4. Precision die-shearing capability allows the fabrication of unusually accurate foil masks (small square part under ruler). Critical dimensions were held to tolerances of ± 0.0025 mm.

to alter the punch design to cause a progressive shearing of the work. A spherical radius offset from the centerline was ground on the cutting surface of the punch to produce the desired effect.

The die was made with a 0.04-mm interference with the punch. After a precision alignment of the punch and the die in a rebuilt Danley die set, the punch was used to broach the die to its final size.

We have improved the state-of-the-art capability in complex shape precision die manufacturing. The first prototype of the design made parts that easily met dimensional requirements. We believe it would be possible to extend this process to spherical shapes.

(For further information, contact William E. Spruit, Ext. 28673, John C. Fry, Ext. 27607, or Donald L. Kyser, Ext. 27607.)

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ENERGY SYSTEMS ENGINEERING DIVISION

We provide the Mechanical Engineering support required to carry out the goals of the laser (Y) program. Briefly, the Y-Program activities can be divided into two categories: 1) *Advanced Isotope Separation (AIS)*: This program uses the unique properties of coherent laser light to selectively photoionize atoms of a given isotope in a material containing several different isotopes. The ionized atoms can then be separated and enriched through the use of extractor/collectors. A long term goal is to demonstrate cost effective enrichment of ^{235}U at product rates that are applicable to commercial production plant requirements. 2) *Laser fusion (LF)*: This effort is directed in the short term at understanding the basic physics problems associated with using high power lasers to implode small fusion targets, while the long term goal is to develop the fusion process to provide an unlimited source of cheap and environmentally acceptable power.

Both AIS and LF are relatively new programs, and they are operating at the forefront of technology. Each advancement toward a program goal or completed milestone represents an extension of the state of the art in engineering and science. We will illustrate this state of the art by citing two examples of the kinds of things that are under development in Y-Program and in which we are involved. In AIS, we are involved in the design and experimental activities required to demonstrate a reliable, easily maintained laser and separation module that will provide the basis for a prototype production facility. In LF, we are involved in the design and construction phase of the next generation solid-state laser system, Nova, which is authorized at \$136 million. This system will demonstrate scientific breakeven of laser fusion.

The Mechanical Engineering tasks associated with each area are extremely challenging. Tasks include:

- Design, analysis, and fabrication of a space-frame structure that will support laser arms in precise alignment.
- Design, specifications, and development of:
 - A target chamber to contain the miniature fusion experiments safely while permitting easy access for target loading, laser beams, diagnostics, and debris collection.
 - A large vacuum vessel, electron beam source, and ancillary equipment to vaporize

uranium and the structures to extract the ^{235}U and to contain and collect the separated species of uranium.

- Development and test of complex diagnostic equipment including: streak cameras, beam analyzers, x-ray microscopy, spectroscopy, and rad-chem analyzers.

- Design and prototype demonstration of laser chain components including: amplifiers, oscillators, lenses, mirrors, spatial filters, shutters, vacuum control systems, and gas flow systems.

(For further information, contact Joseph E. Keller, Jr., Ext. 27582.)

Energy Balance Measurements for Shiva Laser Fusion

Measurement of energy converted into the various reaction products and scattered light is crucial in the performance analysis of laser fusion experiments. These measurements develop laser-plasma interaction theory, which ultimately results in increased understanding of laser-target coupling and output.

Measurement of the laser light absorption indicates that for intensities of interest, inverse bremsstrahlung is not the dominant absorption mechanism. Experiments have shown that polarization dependent absorption mechanisms, such as resonance absorption, are important. Scattered light data have shown that mechanisms such as Brillouin scattering exist and are related to such things as laser pulse length. The scattered light polarimetry and spectroscopy indicate the effect of radiation pressure on the steepening of the plasma density distribution in the region of the critical density. All these effects need to be explored in the higher intensity regions expected in Shiva.

A basic goal of any energy balance measurements scheme is to map the different reaction products in space, time, and energy. The Shiva startup configuration is with 30 energy balance modules (EBM), four vertical rows nearly equidistant. The basic configuration of the EBM (Fig. 1) consists of a 1.06- μm scattered light photodiode, a broadband light calorimeter (LC-21), a Faraday cup to measure the ion spectrum and a plasma

FIG. 1. Details of energy balance module.

FIG. 2. Preamplifiers that boost the signal above ambient noise.

calorimeter (LC-27). The EBM may also have either a 7118 A or a 5345 A tuned photodiode to measure the $e/2\omega$ or 2ω scattered light.

The EBM also allows the inclusion of either a plasma sputtering-loss calorimeter (LC-26) or an x-ray calorimeter (LC-29). The x-ray calorimeter requires inclusion of a valve and quick-disconnect flange to allow frequent filter changes. In back of all the calorimeters, as shown in Fig. 2, are pream-

plifiers that boost the signal above the ambient noise to provide unambiguous data. In front of the EBM's aluminum base is a tantalum x-ray shield to protect the diagnostics from direct and Compton scattered x rays. There is an aluminum cover that envelops the EBM for protection from the high background electromagnetic pulses.

The amount of light absorbed by a laser fusion target can be determined either directly by measuring the total energy of the laser-target interaction products (particles and x rays) or indirectly by performing a balance between incident and scattered light. The light energy balance method requires measuring the incident laser energy, the energy scattered back into the focusing optics and the energy scattered in the balance of 4π steradians around the target.

(For further information, contact Stanley S. Glaros, Raymond V. Baritz, or Terry D. Schwinn, Ext. 25385.)

Advances in Cleaning Metal and Glass Surfaces to Micron-Level Cleanliness

Clean surfaces are required in many areas of science—such as vacuum devices, optics, and integrated circuits—to prevent contaminant-related malfunctions. Obtaining clean surfaces has always been more of an art than a science. Part of the problem is defining cleanliness requirements and quantitatively measuring contamination. Generally, surfaces are required to be free of oils and greases,

FIG. 3. High-pressure solvent spraying of component parts is done in this glove box. The floor of the box forms a funnel to carry the effluent to a membrane filter located below the box.

but may still have many monolayers of absorbed gases. For vacuum applications, very low outgassing rates may be required. Other applications may require automatically clean surfaces or particulate-free surfaces. Described here is one basic technique for cleaning surfaces.

We have developed a high-pressure 6.9-MPa liquid-spraying technique (Fig. 3) to remove small ($>5 \mu\text{m}$) contaminant particles from large (100 m^2) surface areas. Chemically polished and etched 304 stainless-steel components are solvent sprayed to achieve cleanliness levels of less than 10 particle/ cm^2 $5\text{-}\mu\text{m}$ diameter. The high-pressure and high-liquid-velocity cleaning technique can remove 99.9% of $>5\text{-}\mu\text{m}$ -diam particles in 5 to 10 s compared to only 20 to 60% $>5\text{-}\mu\text{m}$ particles by ultrasonic cleaning in 2 to 10 min (Fig. 4).

High levels of particulate cleanliness are required for large solid-state laser systems where contaminants may migrate to optical surfaces and cause severe pitting. The pitted glass must be removed and periodically repolished to maintain acceptable beam quality.

We have also developed special Class 100 clean room procedures and equipment to determine the degree of cleanliness of laser components and to maintain cleanliness during installation and operation. Development of these cleaning procedures resulted in greatly reduced failure rates for solid-state disk amplifiers.

Although developed specifically for cleaning optical components, the basic technique should find wide application in any field requiring particulate-free surfaces.

(For further information, contact Sandy Guntrum, Ext. 26216, Irving F. Stowers, H. G. Patton, C. K. Bennett, G. A. Gleason, J. G. Moore, D. E. Wentworth, E. D. Harms.)

Rapier System for Pulse Compression Updated

The Rapier system is a Raman pulse compression test bed laser based on krypton fluoride laser sources. The KrF systems run efficiently at pulse lengths of several tens of nanoseconds or greater. These pulses are then converted to the short pulse regime suitable for fusion experiments (1 to 10 ns) via backward wave stimulated Raman scattering at the Stokes frequency in a medium such as methane.

FIG. 4. Result of the sequential cleaning of a polished glass substrate contaminated with Al_2O_3 . The substrate was initially ultrasonically cleaned for 1 min in Freon TF, vapor degreased for 1 min in Freon TF, and then sprayed with Freon TF at 340 kPa for 15 s.

The methane serves as a nearly passive conversion medium, converting the KrF input wavelength of 248 nm to the counter-propagating Stokes wavelength of 268 nm.

The system consists of two subsystems: a low energy driver (called the front end) and the electron-beam-driven "A" amplifier (Fig. 5).

In recent months, we have configured the front end as a pulse compressor, and used the output of its electric discharge lasers to produce pulses suitable for an extraction efficiency measurement over small apertures. Conversion efficiencies of about 70% have been observed from the KrF source to the Stokes output, and compression to the 1- to 2-ns regime has resulted.

Meanwhile, the intrinsic efficiency of the "A" amplifier, a 10-by-10-by-50- cm^3 KrF laser pumped from two sides by electron beams, has been measured at about 10%. The result has been about

FIG. 5. Cutaway view of the "A" amplifier showing the laser cell, e-beam diode, and pulse-forming line.

35 J of ultraviolet output in a 50-ns pulse that appears to be spatially uniform. Formal characterization of the output beam quality and ability to propagate the beam will commence shortly.

The full aperture of the "A" amplifier has been injection-locked in an unstable resonator configuration to a narrow band electric discharge laser source. Narrow line width is required for efficient Raman extraction. The parasitic losses, which tend to compete with the injected signal have been sup-

pressed with screens on the top and bottom of the laser, and by stainless steel rods covering the struts that support the e-beam metal foils on either side.

Methane cells are now under construction for Raman compression of the "A" amplifier output using the front end as the driver.

(For further information, contact James C. Swingle, Ext. 26150.)

RESEARCH ENGINEERING DIVISION

The Research Engineering Division (RED) provides the combined skills of engineering and technical personnel to support the following diversified projects:

Applied Energy Technology

Our effort in support of the geothermal program has been to develop the technologies necessary for the utilization of the hot brines of the Salton Sea geothermal field. RED personnel work closely with the program personnel in solving a variety of energy-conversion system problems related to the effects of the high-temperature, high-saline brine. RED has been active in the fielding of experiments in support of the Chemistry effort.

In our solar program, we design, build, and test cost-competitive systems where emphasis is on industrial process heat systems. A strong emphasis of our program is technology transfer; we work with various industries in design studies and prototype system design.

The in situ coal gasification project uses RED personnel in the field experiments that are well instrumented and controlled. RED is involved in subsurface work such as drilling, instrumentation and high-frequency electromagnetic mapping (HFEM) logging and the design, construction, and operation of the surface plant.

In the oil shale project, we are participating in the laboratory testing and modeling of the in situ retorting of oil shale. In order for the future field program to be a success, it must be backed up by adequate chemical and physical analyses of the underground retorting process under controlled conditions. The laboratory experiments require design, fabrication, and operation of retorts as large as 3 ft in diameter.

The spent fuel storage project is a field study to obtain an indication of the feasibility of storing spent reactor fuel assemblies underground in a deep granite formation. RED is involved in the tunneling and drilling work and in the surface and subsurface equipment design. Other aspects include the transportation vehicle design and Quality Assurance program.

Biomedical and Environmental Research

In supporting the biomedical and environmental programs, RED contributes to the research for

detecting, understanding, and minimizing the serious and long-term effects that technology may have on mankind and our environment. For example, RED is involved in the development of new instruments and techniques for rapid and reliable measurement, both physical and chemical, of cells and subcellular particles. We are studying the effects of energy technologies on the environment through monitoring programs (e.g., the geothermal project in the Imperial Valley).

High Energy Physics

We are providing tools with which to pursue the fundamental understanding of energy and matter. Technical support is provided for the experiments performed at the 100-MeV electron linear accelerator (Linac), the RTNS II (rotating target neutron source), the insulating core transformer accelerator, the Van de Graaff accelerator, and the cyclotron.

From the inception of RTNS, RED personnel have been involved in the unique design aspects of this accelerator that provides 14-MeV neutrons for studying the effect of neutrons on fusion reactor-type materials.

Special Projects

RED has a small group working with Z-Division to support DOE's intelligence responsibility. Although this effort touches upon many topics of technical intelligence, the emphasis is on problems dealing with nuclear weapons and nuclear weapon proliferation.

Transportation

RED is providing technical assessment and planning support to the Transportation Energy Conservation Division to assist in the research, development, and demonstration programs. This support covers the following major areas: 1) independent engineering analysis and assessment of new concepts, 2) continually monitoring and making recommendations concerning nonhighway systems, and 3) support of the electric and hybrid vehicle (EHV) program.

The major effort is in support of the EHV program that includes: 1) working with the program office in writing the program plan, the quarterly report, the annual report to Congress and other

program support as requested, 2) conducting a cross-cut analysis to provide R&D objectives, performance specifications, performance models, etc. 3) research and development to conduct proof of principle tests of the dual-mode electric transportation system (DMETS), and 4) participation with the Demonstration and Incentives Branch in the college test program, the proposal evaluations, and the demonstration vehicle on-board data acquisition and reduction module (DARM).

In short, RED is assisting the nation's energy planners in seeking ways to ameliorate our transportation systems' difficulties as the petroleum shortage worsens.

Hazards Control

RED is participating with the Hazards Control department in assuring the safety of laboratory personnel and facilities in the complex and diversified day-to-day activities at LLL.

(For further information, contact Theodore Perlman, Ext. 21417.)

Electrical Discharge in Gases Indicates Conditions of Metals

The mid-19th century saw the advent of a simple device called a discharge tube.¹ This configuration contained two electrodes—a cathode and an anode—separated by some distance in an imperfectly evacuated, nonconducting (glass) container. A voltage applied across the electrodes produced a current flow in the residual gaseous material, which at some point in the applied voltage application, produced luminescence in the gas. This luminescence depended upon the electron emission of the metal cathode for brilliance and the nature of the gas for its distinctive color.

Electron Emission from a Metallic Surface

Electron emission or the probability of electron escape from a metal surface to an adjacent region in a gaseous medium is controlled by the work function (ϕ) of the material.^{2,3} This work function is dependent upon the electron energy inside the material (the volume effect) and surface effects such as chemical contamination and various mechanical and metallurgical surface conditions. It is the surface effects that are of primary interest.

Factors Affecting Surface Electron Emission

Chemical surface effects such as adsorption of foreign atoms on a metal surface modify the configuration of the surface atoms and change the work function.⁴ If the adsorbate is volatilized by the electron-bombardment-produced surface temperature, the effect is not only a change in brilliance of ionized gas caused by electron emission changes, but also a definitive color change caused by the changing chemistry of the ionized gas in the immediate area of the adsorbate.

In the area of metallurgical surface effects, the potential barrier of the surface (work function) is sensitive to the crystallographic orientation of the emitting surface as well as other metallurgical phenomena.³

Mechanical surface effects include the surface texture and surface-related variations caused by internal stresses and strains.⁵ These surface-related variations will affect the emission pattern and this pattern is often recognizable.⁶

Basically we read the gaseous discharge characteristics as indicators of a metal electrode's existing characteristics, particularly its nonuniformities.

Photographic Recording of Optical Effects

Discharge-current-measuring techniques have been suggested as detectors of contamination or surface impurities on metal surfaces. However, these techniques are similar to those used for measuring work function of a surface. They are generally of small electrode area and spacing and must scan the part's surface to present a definitive overall picture. The same multiple factors influence the surface electron emission so the optical whole body photographic techniques are probably better at detecting nonuniformities in large complex geometry parts and are certainly much simpler to use.

Normal color photography using macro and normal lenses is probably the best, most inexpensive recording method. If dynamic recording is justified, then a low light color video system is the answer. In either case the results are spectacular and colorful as well as useful.

Apparatus

Figure 1 shows our version of this time-honored discharge tube. Some conveniences over

FIG. 1. Electrical and mechanical aspects of our discharge tube apparatus.

the basic structure have been added. The glass tubing of 20-cm diameter and 30-cm length is mounted vertically on a gasketed aluminum end plate, which has a motor-driven chuck extending into the chamber. This allows easy change of the cathode structure plus rotational observation of all surfaces. The anode is a copper mesh that can be manually moved to vary electrode spacing inside the supporting glass tubing. Both copper mesh and gasketed aluminum end plate have a central open area of about 8 cm in diameter. This allows viewing of the top of the cathode. A circular glass plate with gasket fills the sealing function in the aluminum anode.

An Example

Figure 2 is fluorescent room light illuminated photograph of a much used electrical connector. The mated connector is about 2.5 by 7.5 by 20 mm. Figure 3 is the same connector but photographed in ionized neon gas. The left-hand spring clip could have plating, chemical contamination, and mechanical deformation problems. The mottled appearance of both spring clips is often characteristic of plastically deformed surfaces. The anomalies are well hidden in Fig. 2—but unmistakably evident in Fig. 3.

FIG. 2. Photograph of an electrical connector taken in room light.

FIG. 3. Photograph of the same electrical connector in Fig. 2 taken in ionized neon gas light. Here we see evidence of probable plating problems and chemical contamination and indications of nonuniform mechanical deformation.

Conclusions

This qualitative technique permits the rapid screening of large number of parts for chemical, metallurgical, and mechanical anomalies. Even though a complete analysis of each observed effect may not be possible, such a technique should be of great value to those in need of a high-speed, non-destructive examination for critical parts. This technique lends itself to completely automating such examinations.

(For further information, contact David E. Lord, Ext. 21270.)

Solar Furnace Provides Heat for Coal Gasification

When carbon is held at a dull red heat in steam, a rapid chemical reaction takes place consuming carbon and producing hydrogen, carbon monoxide, and carbon dioxide. When carbon is heated in carbon dioxide, carbon monoxide is produced. Hydrogen and carbon monoxide are useful as fuels and for chemical synthesis. Under normal circumstances, this reaction cools the carbon rapidly and the reaction stops. The idea of solar coal gasification is to provide the needed heat to keep the carbon hot and to drive the reaction by means of a solar furnace.

In our tests a series of field experiments were carried out using focused solar radiation to gasify coal, activated carbon, coke and a coal plus biomass blend. To carry out such experiments, the incident solar flux must be concentrated by 1000 fold or more. This was accomplished using the White Sands Solar Facility located at the White Sands Missile Range in New Mexico. The maximum power output is about 25 kW which can be focused to a density of about 100 W/cm².

Solar Gasifier Design

Figure 4 shows a sketch of the essential features of the gravity-feed solar gasifier we used at White Sands in June 1979. Constructed of stainless pipe in the shape of an "L," the 30-cm-diam gasifier was lined with firebrick at least 2.5-cm thick to reduce heat loss and to protect the steel from overheating.

About 25 kg of coal chunks or other granular carbonaceous fuel were loaded into the top of the gasifier for each experiment. Then concentrated

FIG. 4. Inside details of the gravity-feed solar gasifier used at White Sands in June 1979.

sunlight was directed onto the bed surface through a silica-glass window 20 cm in diameter. Nozzles located behind the window directed steam or carbon dioxide in a helical path at high speed toward the fuel. Gas flowing in this spiral path acted like a centrifugal separator keeping the window remarkably free of ash and tar.

As fuel was gasified, more fuel could be seen to tumble down the face of the bed to replace it. Ash was melted out of the central focus, the zone of maximum solar flux and temperature. A layer of light-colored ash tended to collect in an annular ring around the hotter central region. This ash ring slowed gasification. The width of the ring of ash accumulation depended on the position of the gasifier relative to the focal plane. In future gasifiers designed for long-term operation, an ash disposal system would be developed.

Objectives and Results

The object of the present gasifier design was to demonstrate the feasibility of solar gasification of coal.

We were also interested in a wide variety of carbonaceous fuels—including oil shale, coke, and biomass fuels. We already have a lot of experience with coal and oil shale from work on other programs here.

Tests conducted at Livermore and White Sands proved a number of important points:

- A solar gasifier with a window in it can be operated for extended periods without fouling the window.

- A medium energy gas (300 Btu/scf) can be produced from coal, coke, and coal-biomass mixtures using the heat flux generated in a solar furnace. The gas was composed of half hydrogen and approximately one quarter each of carbon monoxide and carbon dioxide.

- Oil shale can be successfully retorted using a solar furnace. Further, the solar furnace has the

potential of yielding significantly more hydrocarbon than a conventional retort because the heating rate is faster.

- More work needs to be done on handling material within the retort to get the raw material to the solar beam and to move the residual ash out of the way.

(For further information, contact James R. Taylor, Sr., Ext. 27338.)

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MATERIALS ENGINEERING DIVISION

The Materials Engineering Division (MED) provides complete technical services for mechanical and thermophysical characterization of materials and components and for inspection, evaluation, and proof-testing of complete systems. MED is composed of about 175 people who contribute to the analysis, design, procurement, assembly, and operation of testing systems. Their efforts are directed toward making valid engineering/scientific measurements in support of Laboratory programs and in advancing their expertise through an active program of research and development. The Division has more than 20 separate laboratories and facilities, which are organized into sections responsible for specific technology areas.

The Materials Test and Evaluation Section maintains up-to-date capabilities to provide mechanical testing through application of ASTM standard tests and to conduct special test procedures tailored to individual customer requirements. A high level of engineering and technical expertise is directed at continuing development in the special fields of acoustic emission, fracture mechanics, high-rate response, and composite materials evaluation.

The Engineering Measurements Section provides various kinds of measurements engineering to Laboratory programs, ranging from the calibration of a single transducer to the fielding of complete measurement systems. Service for the calibration and installation of conventional pressure and force transducers and accelerometers is available.

The engineers and technicians of the Non-destructive Evaluation Section provide quality-assurance services and engineering inspection for LLL programs. The work requires extensive liaison and field operations throughout the Department of Energy agencies and field testing centers. Non-destructive evaluation is done with neutron, x-ray, and gamma source radiography, ultrasonics, eddy current, dye penetrant, magnetic particle, and holographic techniques. Precision radiation gaging is available using both through-transmission as well as various backscattering approaches when only one surface is readily available.

The Engineering Design Section designs and fabricates component and system hardware in support of the Chemistry and Materials Science Department, the Earth Sciences Division, and

MED itself. A major effort is support of the tritium facility operation by designing tritium-handling systems, directing associated quality-assured up-grading activities, and developing tritium-certified hardware.

The High Pressure Section provides the necessary technology and facilities for conducting high-pressure gas and liquid experiments. The section is also responsible for providing certified and safe tubing, valves, fittings, and miscellaneous hardware for use in tritium-handling systems. Remote, explosion-safe test cells are maintained for programmatic use, research, and development and for periodic proof-testing of standard hardware as part of the lab-wide Quality Assurance program. High-temperature gas autoclaves are used for diffusion bonding studies and compaction sintering or densification research.

The Computer System Applications Group is composed of personnel with broadly based technology expertise. Their expertise ranges from the design and fielding of computer-based data acquisition and control systems such as the transport data acquisition and control (T-DAC) to research on the mechanical response of complex structures. Another major effort is support of the Weapons Division's environmental testing activities.

The plutonium facility is jointly operated by MED and the Metals and Ceramics Division of the Chemistry and Materials Science Department. The engineering activities are readily grouped into two separate efforts: (1) engineering design, fabrication, and execution of testing in support of chemistry programs and (2) direct weapons program support by fabrication of device hardware and complete responsibility for component tests and evaluations.

(For further information, contact Donald W. Moon, Ext. 28360.)

***In Situ* Packed-Bed Dryer Provides Low-Cost Regenerable Service**

We designed and built a packed-bed drying column for removing moisture from gases using conventional desiccants. It can be used for temporary or emergency service inside glove boxes or

other chambers without any additional plumbing or connections. Special features of the unit are:

- High performance.
- Exceptionally low cost.
- Easy regeneration.

The last two features are especially desirable when removing tritiated (radioactive) moisture.

Such a dryer was needed because of problems we encountered in decommissioning an 8-m³ glove box after tritium service. The gas purifier (24 liters/s) for this glove box included a 136-kg bed of type 5A molecular sieve desiccant. This bed was nominally quite dry, but the necessary use of normal water (H₂O) for cleaning the glove box would have caused some of the tritiated water (HTO) already on the bed to be released. The bed could not be regenerated to prevent this effect.

To eliminate water contamination of this bed, we designed an inexpensive desiccant bed. It processes at nearly the same rate as the 136-kg bed, although its total capacity is limited. It is regenerable simply by pouring out the expended material and replacing it with fresh material. In effect, this gives us an unlimited capacity to absorb H₂O that contains some HTO.

Placed inside the glove box on the floor, this dryer continuously circulates and dries the glove box atmosphere. Since the suction and exhaust are both inside the glove box, no other connections or plumbing are needed. The unit has been used in both air and argon atmospheres; it is operated as a packed bed, using conventional design parameters to predict performance.

The dryer is constructed as shown in Fig. 1. A small blower is bolted to a lard can to provide gas flow to a chamber. The blower was chosen to provide flow of about 20 liters/s through a 5-cm-deep, 30-cm-diam bed of 3-mm desiccant pellets, with about 0.2 kPa pressure drop. A 16-mesh wire screen mounted across the inside of the can is the base for the desiccant bed. Joints are sealed with Silastic adhesive.

We used type 5A molecular sieve desiccant. In practice, a 2.3-kg charge gave a bed 5 cm deep with a maximum capacity of about 460 g water. We normally limited the amount of water used at one time, to assure satisfactory operation. As a second control, we sprinkled Drierite (a CaSO₄ desiccant that changes color when saturated with water) on the exhaust side (top) of the bed to show when the bed became saturated.

In the glove box described here, a fresh charge of molecular sieve could maintain the atmosphere at 250 ppm H₂O. It could also reduce the moisture in the box from about 30 000 to 2000 ppm in less than 2 hours. We found that HTO buildup as an isotopic form of water was limited to less than 6 Ci/m³. These levels could be tolerated readily without undue hazard to personnel.

The dryer was designed for disposal in contaminated waste after use. The desiccant charge can be stored indefinitely in sealed containers, which makes the dryer especially suitable for emergency service; it can be put into service as fast as the desiccant can be poured into it. Total cost was well under \$20; all parts were obtained from LLL stores. Assembly time was about 2 hours. Each molecular sieve charge costs about \$17. We believe these exceptionally low costs are unprecedented for a dryer that performs so well.

(For further information, contact Richard L. Stark, Ext. 27977.)

Properties of High Explosives Now Measurable with Few Samples

We have developed a method that uses ring-shaped samples of high-explosive materials (HE) to characterize their thermomechanical properties. The method is unique in integrating computer stress-analysis codes and statistical strength theory for data interpretation.

The advantage of using stress-analysis codes and data analysis of mechanical tests as an integral package is that the material constituent constants (i.e., moduli, strength, etc.) are automatically optimized for the computation code. It follows that the predictive accuracy would be high if the geometry and stress state of the laboratory tests were homologous to those of the actual structure. Using the ring geometry, we have various loading configurations (shown in Fig. 2) to facilitate adjusting the stress state to be similar to that of the actual structure.

The advantages of this sample geometry are that the volume of the sample is small, fabrication and testing are simplified, and one geometry serves for all tests. Our method allows us to determine from a limited number of samples (as few as nine) the following properties:

FIG. 1. Packed-bed dryer for use inside glove boxes requires no additional plumbing or connections.

- Initial stiffness (elastic moduli).
- Time-dependent stiffness (viscoelastic moduli).
- Time-dependent failure kinetics (stress-rupture curves).

- Failure statistics (Weibull shape and scale parameters).

- Size effect (strength dependency on material volume).

The method is applicable to diagnostic screening in

FIG. 2. Ring geometry allows several loading configurations.

HE synthesis, measurement of constitutive properties, quality assurance testing in HE production, and monitoring of aging and compatibility.

We have developed the procedure for diagnostic screening using the compression geometry shown in Fig. 2 (the other configurations can also be implemented); the results illustrate some of our methodology. In this test, a ring sample is loaded in compression (see Fig. 3) at constant loading rate to failure. The applied load and displacement along three diametric positions are recorded by a minicomputer-based data acquisition system. By analyzing the sample configuration with the NIKE2D structural analysis code, we can determine the modulus and the Poisson's ratio from the load and displacement measurements.

Three groups of samples are subjected to loading rates that induce failure in 1, 100, and 10^4 s.

The decrease in strength as a function of loading rate can be related to stress-rupture; an example of this operation is shown in Fig. 4, where the time-to-failure curves were obtained by convoluting the data at different failure times back to a reference time (1 s in this case) using a power law relation. The statistical parameters (the Weibull scale and shape parameters indicated in Fig. 4) are estimated using the maximum likelihood method. The scale parameter can be loosely interpreted as the mean strength and the shape parameter is approximately equal to the inverse of the coefficient of variation. With such curves, we can extrapolate long-term life (about 10^5 to 10^6 s) from short-term tests that take only a few hours.

This pooling of data at a reference time also provides an estimate of the probability of survival as a function of applied stress level. An example of

FIG. 3. Compressive ring test of HE: extensometers measure three diametrical displacements.

FIG. 4. Time-to-failure stress-rupture curve, estimated from testing HE (RX03-BB) at three loading rates.

one use for this is shown in Fig. 5: probability-of-survival curves are given for two batches of HE, one manufactured by a large-scale process and the other by a small-scale process. The coincidence of the curves at high stress (or low probability-of-survival) levels confirms that both batches have the same intrinsic strength. Conventional methods of comparing the mean strength would have arrived at the erroneous conclusion that the large-scale-process batch is stronger. As can be seen in Fig. 5, however, its higher mean strength is actually a consequence of smaller scatter, which is attributable to manufacturing and handling.

These examples illustrate the wide range of information we can extract from a small number of samples.

(For further information, contact Edward Wu, Ext. 26937; William W. Feng, Ext. 28701; Jay K. Lepper, Ext. 26372; or Don Breithaupt, Ext. 27758.)

TRAAP: Additions to LSI-11 Capability for Transient Recorders

We have added to MENU, the LSI-11 data acquisition and reduction program used with the transient recorder. The transient recorder can record six channels of data at a selected sweep duration, from 1 ms to 8 min. Typically the Materials Test and Evaluation Section uses it with a high-rate test machine for test durations of less than 1 s. We intended to complete 6 of 19 additions by July 1979.

Because the limited core memory of the LSI-11 could not accommodate that number of additions, we had to restructure MENU. During this operation, it became obvious that not all of the six additions were practical or necessary at this time. We completed three of the six:

- x-vs-y plotting (plots channel vs channel, such as load vs displacement).
- Curve smoothing (removes low-level noise or averages steps in data).

- Zero offset removal (removes unbalance conditions from bridge-type signals).

Four other programs from the original list are also completed:

- Zoom plotting (graphs a specified area with magnified scale values).

- Multichannel averaging (sums a specified number of channels of a particular type, and divides by that number).

- Inverse FFT (converts data from frequency domain to time domain).

- Data clipping (limits unwanted large data signals to a selected level).

We chose a more descriptive name, TRAAP (transient recorder-acquisition-analysis-plotting), to replace MENU. An added benefit of the restructuring is that data recorded by the Engineering Measurements Section can be analyzed and plotted with TRAAP. Further additions will be made as time permits.

(For further information, contact George Yanes, Ext. 27089.)

Surge-Damping Valve Protects Fragile Vacuum Systems

Flow surges are very common in vacuum systems—they are usually inconsequential, but in

FIG. 5. Probability of survival of two batches of HE (RX03-D1), showing that both have the same intrinsic strength; difference in apparent mean strength is attributable to the amount of scatter.

some systems they can damage sensitive apparatus or fragile parts. Surges can also contaminate vacuum pumps by sweeping unwanted materials into them. We have developed an automatic surge-damping valve that can be used in most vacuum systems.

The valve could be incorporated in several places on the roughing side of a vacuum system. Almost maintenance-free, it does not need manipulation or an internal power source. It could protect fragile windows under vacuum in line-of-sight pipes, for example, or glass vacuum systems.

The mechanism, shown in Fig. 6, contains a disk with several narrow peripheral slots. The disk is mounted on the end of a shaft centrally positioned by a spider (insert). Under normal flow conditions, the spring forces the disk against the tabs on the perforated ring within the valve body. Under surge conditions, differential pressure seats the disk against the pump-side fitting and reduces the flow area to just the narrow slots in the disk.

Installation may reduce the conductance of a vacuum line because the gas must take a circuitous path through the valve and because the annulus may be smaller in area than the inside diameter of the vacuum line. If this becomes a problem, an electromechanical bypass system can be installed and actuated by the opening of the valve.

We tested the valve by mounting it on a 90-degree bellows-type vacuum valve, which in turn

FIG. 6. Automatic valve uses a slotted disk to reduce surges in vacuum systems.

was mounted on the inlet to the roughing pump. When the vacuum valve was opened, the surge-damping valve closed and did not open again until the system was equalized at about 1000 Torr. The system then pumped down normally to its base pressure.

The valve is now in use in several vacuum systems at LLL and would probably be effective in many others. Note, however, that it is not a check valve; it does not totally interrupt the flow.

(For further information, contact Jack C. Bullock, Ext. 28042.)

Calibration Service Ensures Accuracy of Torque Tools

Torque wrenches and torque screwdrivers need periodic cleaning, adjusting, and calibration to assure operational accuracy. MED set up a calibration program in June 1978 to perform these services for LLL personnel. Anyone using torque devices,

especially in critical or quality-assurance operations, should use this service for calibration and recall.

Even newly purchased tools require calibration. For example, one new torque wrench we tested was actually out of calibration over 50% of its usable range (see Table 1).

TABLE 1. Before- and after-calibration data (ft-lb) for torque wrench tested by the MED calibration service.

Optical torque tester	Precalibration	Average of three tests after adjusting the range
15	16	14
30	31	30
50	52	50
60	63 ^a	60
70	73 ^a	70
80	84 ^a	79
90	94 ^a	90
100	106 ^a	100

^aOut of tolerance.

A tool submitted to the service is cleaned, repaired if necessary, and calibrated so that it indicates a torque accurate within 2% of its full-scale torque. Accuracy is traceable to National Bureau of Standards. Calibrated devices are labeled to indicate the calibration and recall dates; the user receives a calibration certificate that shows test data taken before and after calibration.

The service uses a computerized system to notify the user when the device should be resubmitted for routine calibration. The device is usually returned within 10 working days after being submitted. In emergencies, a shorter turnaround time is possible.

Implementation procedure MED 78-128 and Specification MEL 77-001366 give the details of the program.

(For further information, contact Joseph D. Cervelli, Ext. 29598.)

Automatic Calibration of Data Channels

The Computer System Applications Group is developing an interactive computer-run control, calibration, and data acquisition system for the dynamic testing facility at Site 300. A Modcomp IV controls a shaker command unit, a calibration unit, and several data capture units to accomplish these tasks and present real-time results on a CRT console.

Because the causes of signal degradation in the data acquisition network are frequency-dependent, it is essential that the system be calibrated dynamically. The computer program to do this automatically and to measure the 60-, 120-, and 180-cycle noise in each channel has been written and installed.

The program uses a weighted least-squares estimation procedure derived from optimal control theory.¹ The calibration signals are sinusoidal and square waves that are injected into the data channels in the test cells and captured after traversing the normal data path. Noise identification is performed in the same manner but with a zero or purely DC input. Because the phase value of each signal is determined in the process of solving for the amplitude, the noise can be removed from recorded data without using filters.

Operation of the calibration program is designed to be as automatic as possible. The user indicates the type of analysis to be performed (sine, square, or noise) and the data channels involved. The program then accesses a data base to determine the type of transducer on each channel, injects, captures, and analyzes the appropriate waveform, and displays the results.

Analysis of artificial data indicates identification with error less than 0.5% is achieved with parameter values set to those seen at Site 300. While the results of processing real data cannot be quantified as easily, the absence of patterns in the residuals (the difference between the captured data and the model) and the repeatability of results indicate that the analyses are reliable.

(For further information, contact Edwin E. Nesbit, Ext. 21728.)

Pressure Vessels Examined by Holographic Interferometry

Holographic interferometry is a nondestructive testing technique that has been used successfully to evaluate the performance of fiber-reinforced pressure vessels.^{2,3} We used this method to examine three NASA experimental gas-storage vessels under stress. The vessels were Kevlar/epoxy (100/44.7) wound over 1-mm-thick aluminum spherical mandrels; each mandrel had electron beam welds at the waist, the fill tube, and the opposite pole plug.⁴ The holographic interferograms supplied information on failure modes, displacement profiles, and possible fiber damage.

The critical configuration of the interferometer is shown in Fig. 1. It allows two holograms to be made simultaneously, so that nearly 360 degrees of the vessel can be examined. We used a double exposure technique; each exposure was made at a constant pressure, which increased between exposures. The reconstruction of each double exposure hologram consists of an interference pattern superimposed on an image of the object; we call this the fringe pattern.

All three vessels had a design burst pressure of 34 MPa. Vessels A and B had been pressurized previously to 31 MPa and 20 MPa, respectively, for acoustic emission testing. We ran two test cycles (to 4.8 and 22 MPa maximum pressure) on these two

FIG. 7. Optical configuration of holographic interferometer. PH = plate holder, M = mirror, BS = beam splitter, SF = spatial filter, BB = beam block, VA = variable attenuator.

vessels, making several holograms during each cycle, to seek evidence of possible damage caused by the previous pressure test. We then tested all three vessels to 31 MPa in an attempt to produce limited damage to the Kevlar fiber.

Comparison of fringe patterns showed only minor variations in the displacement profiles of the three vessels. Three significant aspects of the vessel design were revealed by the tests:

- The fringe patterns show that symmetric displacement patterns occurred about the two poles. Displacement profiles calculated from the fringe patterns (by conversion to surface displacement vectors) show that the vessels expanded with axial symmetry during pressurization. For example, Fig. 8 gives the waist and pole-equator displacement profiles for vessel B; the pole (fill tube) region displaced twice as much as the waist region, and the displacement field was symmetric about the fill tube. Previous work found that the poles were usually the site of failure during burst tests.⁴ Thus the fringe pattern around the poles might be a useful measure of vessel strength.

- Failure of vessels may occur in two ways. In these tests, vessels failed because of cracks in the

aluminum liner—not because of bursting (failure of the Kevlar/epoxy matrix), which was not studied here. Leaking of hydraulic fluid obliterated part of the fringe pattern, but the visible symmetric portions indicated that the vessel was maintaining strength even though the liner was leaking. (Gamma radiography subsequently revealed the cause of leakage to be cracks in the liner at the plug weld opposite the fill tube.)

- Matrix crazing may be revealed by a biconvex fringe pattern. During testing of vessel C to 31 MPa, leaking occurred at 13.8 MPa and the test was stopped. Upon a subsequent pressurization several biconvex fringe patterns (see Fig. 9) were noted. The pattern is aligned with the fiber winding direction and occurred at a pressure where delamination and fiber breakage do not normally occur. If, as suspected, it is a result of matrix crazing, the quantity and location of such patterns may be useful in predicting the stress resistance of vessels. We plan more tests, using combined holographic interferometry and acoustic emission, to better characterize these pressure vessels.

(For further information, contact Donald M. Boyd, Ext. 27971, or Bruce W. Maxfield, Ext. 27969.)

(a)

(c)

(b)

(d)

FIG. 8. Fringe patterns and the resulting radial displacement contours (along indicated contours) for vessel B: (a) fill tube to waist, (b) around waist weld. (Note: the aluminum liner affects the fringe pattern.)

FIG. 9. Biconvex fringe patterns indicating possible matrix crazing of vessel C.

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MAGNETIC FUSION ENGINEERING DIVISION

The Magnetic Fusion Engineering Division (MFED) supports LLL's physics programs in three principal areas:

- Magnetic fusion energy (MFE) confinement experiments.
- MFE development and technology.
- Particle beam development.

Although their goals differ greatly, the three areas share a common technology base. Support is needed from virtually all mechanical engineering disciplines, as well as from the following specialties: normal and superconducting magnetics, cryogenic systems, vacuum systems, and high voltage components.

Our role in MFE confinement experiments is to provide the systems engineering, design, and fabrication of mechanical hardware. Ultimately, this research in the magnetic confinement of nuclear fusion reactions is expected to lead to tapping deuterium, an isotope of hydrogen present in sea water, as a nearly inexhaustible energy source. The major confinement experiments are designated TMX, Beta II, and MFTF; together they represent a total program cost well over \$140 million.

In MFE development and technology, our mission is to develop the technology base and engineering skills necessary to meet the future needs of magnetic confinement systems. Currently we have active programs in multifilamentary Nb₃Sn superconductor development, high vacuum technology, neutral-beam source development, and fusion reactor studies. Basic research and development are emphasized to lay the groundwork for future fusion experiments.

The particle beam development program, funded by the Defense Advanced Research Agency (DARPA), involves building high-current, high-voltage, electron accelerators. Such accelerators are of interest in basic physics research and the weapons community. The present program calls for development of two accelerators, the Experimental Test Accelerator (ETA) and the Advanced Test Accelerator (ATA). The ETA program is the predecessor to ATA, and will generate the technology data base to build the 10-kA, 50-MeV ATA machine.

(For further information, contact Dennis K. Fisher, Ext. 26750.)

Fusion Chamber System Cryopanel Designed for Mirror Fusion Test Facility

The east structural ring of the Mirror Fusion Test Facility (MFTF) fusion chamber system (FCS) was placed on its support legs in August 1979. Figure 1 shows the ring in place. The FCS will house and provide the necessary environment for the MFTF superconducting magnet, neutral beam injectors, plasma streaming guns, and other equipment for starting up, sustaining, and controlling a fusion plasma.

The major subsystems of the FCS are listed in Table 1. The cryogenic subsystem of the FCS provides liquid helium at 4.5 K to cool the magnet and the cryopanel. The external vacuum subsystem pumps the vacuum vessel from atmospheric

TABLE 1. Major subsystems of the fusion chamber system.

Vacuum vessel system	
18 m long, 10.5 m in diameter	
Provisions for: magnet suspension, plasma diagnostics systems, support systems interfaces, access and maintenance, neutral beams and streaming guns systems	
Cryopanel system	
High-speed vacuum pumping of deuterium (D ₂)	
External vacuum pumping system	
Roughing pumps (air, D ₂ , H ₂ , He)	
Liquid helium cryo-condensing vacuum pumps (air, D ₂ , HD)	
Liquid helium cryosorption pumps (H ₂ , He)	
Cryogenic system	
Closed-loop liquid helium refrigerator/liquefier (3075 W, 600 liters/h)	
Open-loop liquid nitrogen system (5000 liters/h)

FIG. 1. East structural ring of the MFTF fusion chamber system in place; its total lift weight is 59.2 tons.

pressure to 10^{-6} Torr vacuum pressure and is also used in cryopanel generation.

The vacuum vessel (major features are given in Table 1) provides the vacuum environment for the plasma within which the fusion reaction occurs. Because the flow rates of injected gas from neutral beam injection and plasma stabilization sources are very high (2220 Torr-liters/s), maintenance of the high-vacuum environment requires large-scale cryopanel pumps. The gas load is primarily deuterium, so condensing surfaces operating at 4.5 to 5 K are required.

We have made good progress in developing this cryopanel subsystem. Using the LLL-developed three-dimensional Monte Carlo code, we evaluated two similar cryopanel pump configurations: W-shaped and Z-shaped. These shapes refer to the configuration of the liquid-nitrogen-cooled radiation shields that protect the liquid-helium-cooled cryopanel pump surfaces. The W-shaped configuration is shown in Fig. 2.

Advantages of the W-shaped and Z-shaped cryopanel pump configurations are:

- The liquid-helium-cooled 4.5 K pump panel is optically tight to an external plane surface that is coincident with the surface of the cryopanel module.

- The panel pumps from two sides and has a very high capture fraction. The mathematical prediction of a 0.27 capture fraction for the W configuration compares well with experimental data from the test panel in Fig. 2, which indicated the range 0.25 to 0.27. A 0.31 capture fraction is predicted for the Z configuration.

- Manufacturing tolerances involved in assembling the liquid-nitrogen-cooled shield panel to the liquid-helium-cooled pump panel are much less critical than those for other designs. This is because the manufacturing tolerances that affect proper shielding apply only to the assembly of each shield and pump set, not to the manufacture and assembly of a cryopanel module or the cryopanel arrangement.

- Because the cryogenic cooling passages are all circular pipes, no special treatment is required for cryogenic engineering design of flow distribution, pressure drop, heat transfer, or pump panel surface temperature.

- Arrays of both configurations are easily fabricated from aluminum extrusions. They are precise and uniform, rigid and durable.

FIG. 2. A W-shaped cryopanel test panel during fabrication, shown with the helium manifold covers removed. The pumping surface on each side is 52 in. wide and 96 in. long.

- Because of the relative insensitivity of the W and Z configurations to manufacturing tolerances, we expect dependable long-term performance of the cryopanel system in spite of the rigors of installation, removal, and reinstallation and the entry of MFTF maintenance personnel into the vacuum chamber between tests.

Between plasma buildups in the MFTF, we must provide a vacuum of 10^{-8} Torr and remove impurities to aid the next plasma startup and stabilization processes. Besides cryopanel pumping, fresh titanium atoms are deposited on the surfaces of the magnet liner to provide pumping or "getter" action. This layer is particularly effective in pumping energetic neutrals during the plasma "burn" time. The getter system includes a number of titanium/tantalum wires, approximately 2.5 m long, inserted into the plasma chamber and plasma fan region and heated to evolve the fresh titanium. The power supply is capable of heating the wires in a magnetic field ranging from 2 to more than 4 Tesla, depending on the location within the yin-yang magnetic environment.

(For further information, contact William H. Strebentz, Ext. 21494.)

Parametric Studies of Tandem Mirror Reactors

The major goal of our tandem mirror reactor studies since the preliminary design report¹ has been to improve reactor performance while simultaneously lowering the level of required technology (mainly for neutral beams and magnets). Ideas that have been investigated are the addition of "A" cells, direct electron heating, and thermal barriers to insulate the plug electrons from the central cell electrons.²

"A" cells are auxiliary plasma cells placed at each end of the tandem mirror, outside the plug cells. Their purpose is to improve the confinement of the plug plasma by reducing its outward potential drop. The required injection power for the "A" cell can be very small, and the net benefit is a reduction in plug injection energy and/or improved performance.

Direct electron heating in the central cell allows a further reduction in injection energy and improvement in performance. Electron cyclotron resonance heating (ECRH) in the central cell could be done at the microwave frequency of gyrotrons under development (≤ 110 GHz). Direct electron heating in the plugs by ECRH would require higher frequency gyrotrons, but would further reduce the required injection energy and further improve performance.

The thermal barrier concept, a very new idea, is discussed in detail in Ref. 3. Basically, it uses a lowered plasma potential between the central cell and plug to serve as an electron thermal barrier between them. Electron heating in the plug can then result in a higher electron temperature there and improve tandem performance greatly. The effect of the thermal barrier is so strong that large relaxations of technology can be made. Reduced plug magnetic field and plasma density allow ECRH heating in the plug in the range 55 to 110 GHz.

Parameters for three tandem reactors are listed in Table 2. The first reactor, discussed in Ref. 4, is an unoptimized design that uses "A" cells and direct electron heating in the central cell. The injection energy is reduced from the 1200 keV specified for our preliminary design,¹ but the plug magnetic field strength is very high.

The second reactor is an optimized design with "A" cells and direct electron heating in the plugs. The beam energy and the magnetic field strength are reduced significantly from those for the first design. The plasma Q is the same, but the first-wall neutron loading is more than twice as high.

The third reactor, a preliminary unoptimized design that incorporates the thermal barrier concept, shows striking improvements over the other two. The neutral beam injection energy is reduced, and only 10 MW of beam power is required. The

TABLE 2. Parameters of three tandem mirror reactors.

	"A" cells and central cell electron heating	"A" cells and plug electron heating	Thermal barriers
Neutral beam injection energy, keV	600	350	200
Plug magnetic field strength, Tesla	19 or 21 ^a	15 or 17	12
Neutral beam power, MW	80	42	10
Electron heating power, MW	130	250	57
Fusion power, MW	2100	3000	1500
Length of central cell, m	240	320	50
First-wall radius, m	1.9	0.9	1.1
Plasma Q ^b	10	10	23
First-wall neutron loading, MW/m ²	0.6	1.3	3.6 ^c

^aThe lower value is for a simple mirror plug (i.e., MHD stabilization by the "A" cell), the higher for a Yin-Yang plug.

^bBasic plasma performance quantity, equal to the fusion power divided by the trapped injection power from all external sources.

^cThis value can be reduced by increasing the first-wall radius, if such proves cost-effective in terms of wall lifetime.

magnetic field is reduced and the plasma Q is increased. The reactor is also attractively dimensioned, with a much shorter central cell.

Clearly, the thermal barrier concept can result in a superior reactor. Our analytic zero-dimensional physics model must undergo a major modification to include thermal barriers; we can then do more accurate calculations and begin to optimize a design. We also must investigate fully the technology requirements of thermal barriers. If these studies show that the parameters in Table 2 are possible, we can achieve attractive tandem mirror performance with reduced technology requirements.

(For further information, contact Gustav A. Carlson, Ext. 26728.)

References

1. R. W. Moir, *et al.*, *Preliminary Design Study of the Tandem Mirror Reactor (TMR)*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-52302 (1977).
2. G. A. Carlson, *et al.*, *Parametric Studies of Tandem Mirror Reactors*, Lawrence Livermore Laboratory, Livermore, CA, UCID-18158 (1979).
3. D. E. Baldwin, B. G. Logan, and T. K. Fowler, *An Improved Tandem Mirror Fusion Reactor*, Lawrence Livermore Laboratory, Livermore, CA, UCID-18156 (1979).
4. B. G. Logan, *et al.*, *Tandem Mirror Reactors*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-80644 (1978).

MATERIALS FABRICATION DIVISION

The Materials Fabrication Division, a multi-disciplinary organization within Mechanical Engineering, provides services that are not available from commercial sources. The number and diversity of LLL research efforts make this Division one of the Laboratory's largest. We have about 400 highly skilled personnel and more than 3700 pieces of equipment in our \$13.5 million inventory. Our facilities provide special capabilities in the fields of optics, welding, vacuum process, glass, plastics, sheet metal, metal finishing, metrology, pressing, inspection, and assembly, as well as conventional and numerically controlled machining of metals, high explosives, and ceramics.

In-house fabrication services are available to all LLL programs when program requirements call for:

- Fabrication capabilities not readily available elsewhere.
- Rapid turnaround times.
- Handling of materials that are toxic, radioactive, or classified.

In addition, the facilities are used to develop improved manufacturing techniques and to advance machine tool research. Our operating philosophy is to satisfy the mechanical fabrication need of the programs, consistent with priorities set by those programs.

(For further information, contact Robert A. Berg, Ext. 27643.)

New Inspection Instrument Has Minimum Stylus Force

We have developed an improved air-bearing linear variable differential transformer (LVDT) for inspecting precision parts made on diamond turning machines and parts of many precision instruments.

It uses less stylus force and less friction than its predecessors, to protect the diamond tip in tool-setting operations (where a force >0.2 g will damage the cutting edge) and the high-quality finishes of the parts it inspects.

LVDT's use an iron core in a field coil to convert axial displacement of the plunger/core assembly into a voltage output. This voltage signal is amplified and read as linear displacement, at ratios of up to a million to one.

The need for an LVDT with these features became apparent with the advent of the diamond turning machine. The original LLL design resulted from a lack of commercially available devices. Friction caused by the anti-rotation mechanism in this LVDT was reduced in a second design, but radial stiffness was insufficient to measure accurately in x-y coordinates. The third, and final, design shows superior performance; changes reduced the difficulty and cost of manufacture and corrected some secondary technical problems. The advantages of this LVDT are:

- Lowest stylus force.
- Amplifier compatibility.
- Uses standard coil.
- Excellent anti-rotation.
- Good radial stiffness.
- Stylus force adjustable from <0.1 g to >10 g, with no variation in force throughout the travel of >0.1 in.

This device is more accurate than others now on the market, and costs slightly less. Prototypes have been assembled and tested; plans are to produce 24.

(For further information, contact Herman W. Hauschildt, Ext. 27603.)

PUBLICATION ABSTRACTS

Michael A. Gerhard, *OASIS: A General Purpose Mesh Generator for Finite Element Codes*, Lawrence Livermore Laboratory, M-101 (1979).

OASIS is a general purpose mesh generator for two- and three-dimensional finite element codes. The basic parts of OASIS are the surface generator and the three-dimensional region generator, both of which use a linear-blending interpolation formula.

Two coordinate systems are used, integer space and geometric space. Integer space is defined by a righthanded coordinate system (I,J,K), and represents rectangles in two dimensions (2D) and rectangular prisms in three dimensions (3D) (Fig. 1). A node in integer space has three integer coordinates. On the other hand, geometric space is defined by a righthanded orthogonal coordinate system (X,Y,Z); the structure actually exists in geometric space (Fig. 2).

In 2D, OASIS is able to generate triangular transitional elements, 4-node isoparametric elements, 5-to-9 node continuum elements, bars and beams. In 3D, OASIS can generate 8-node isoparametric elements as well as 9-to-27 node continuum elements and trusses. In 2D, a standard quad element may degenerate into a triangle. In 3D, a standard brick may degenerate into a triangular pyramid (Fig. 3). In both 2D and 3D, displacement, rotation, and traction boundary conditions may be applied.

R. C. Murray, *LX-09-0 Composition Variable Study*, Lawrence Livermore Laboratory, UCID-18081 (1969).

The purpose of the test program was to establish the mechanical properties variation within the production composition range. Any useful information that may influence specification writing or improve production and quality control will be examined. Batches PX303 through PX307 were all made with Aerojet DNPA, while batch PX308 was made with Hummel material. All batches were made with the same HMX and EFO. Pressing conditions were similar in all cases.

G. A. Carlson, B. M. Boghosian, J. H. Fink, J. O. Myall, and W. S. Neef, Jr., *Parametric Studies of Tandem Mirror Reactors*, Lawrence Livermore Laboratory, UCID-18158 (1979).

This report, along with its companion, *An Improved Tandem Mirror Reactor*, discusses the recent progress and present status of our tandem mirror reactor studies. This report presents the detailed results of parametric studies up to, but not including, the very new ideas involving thermal barriers, which are discussed in its companion.

R. W. Werne, *Structural Response of VRO and FKM Propellants During a Rocket Motor Implosion*, Lawrence Livermore Laboratory, UCID-18160 (1979).

As part of the LLL effort on the Trident program we were asked to perform comparative calculations simulating an implosion scenario which is thought to have occurred during a test of a scaled version of the first stage Trident rocket motor. The primary purpose of the calculation was to compare the relative performance of two propellant formulations, designating VRO and FKM, respectively. The difference between the two formulations manifests itself in their respective constitutive models.

Dean B. Tuft, *Calculation of Laminar Incompressible Fluid Flow and Heat Transfer During Spherical Annulus Filling*, Lawrence Livermore Laboratory, UCID-18168 (1979).

A method of computing laminar incompressible fluid-flow and heat transfer during the filling of a spherical annulus is presented. Transient fluid temperatures and heat flux rates in the spherical annulus are calculated for an insulated outer sphere and a constant temperature inner sphere with heated water filling the annulus from the bottom.

To achieve a solution, laminar axially symmetric flow is assumed and the Marker-and-Cell (MAC) free surface computational method is applied to this problem in spherical coordinates. Changes in the standard MAC treatment are incorporated and special methods for handling the free surface are introduced. A variable mesh is used to improve resolution near the inner sphere where temperature and velocity gradients are steep and the governing equations are derived for variable fluid properties to allow an eddy viscosity turbulence model to be applied later.

Calculations of velocity, temperature, and inner sphere heat flux in a spherical annulus of 139.7 mm inner radius, and 168.3 mm outer radius within an inlet tube diameter of 38.1 mm are presented. The inner sphere is held at 0°C and the inlet water temperature is 50°C. Laminar results corresponding to an annulus fill time of 20 seconds are presented and the major features of the flow are discussed.

Computed separation point location is compared to experimental results from the literature. Differences in computed and experimental separation point location are shown to be a result of turbulence in the calculations. Calculated flow patterns are in qualitative agreement with steady flow experimental observations in the literature.

C. Y. Liaw, A. M. Davito, and R. C. Murray, *Seismic Analysis of the Acid Liquid Waste Tanks at the Western New York State Nuclear Service Center, West Valley, New York*, Lawrence Livermore Laboratory, UCRL-52600 (1979).

This report was prepared at the request of the Nuclear Regulatory Commission as part of a review of the nuclear fuel reprocessing plant operated by Nuclear Fuel Services, Inc., at West Valley, N.Y. The report discusses the seismic evaluation by Lawrence Livermore Laboratory of two high-level, acid liquid-waste tanks, 8D-3 and 8D-4, adjacent to the plant. It describes the tanks and discusses the techniques used to model and analyze the structures and to combine the loads. Limiting criteria, results, and conclusions are presented.

G. M. Taylor, *X-Ray Microdensitometer (XRPD) Performance Characteristics*, Lawrence Livermore Laboratory, UCRL-52657 (1979).

The Nondestructive Evaluation Section of Lawrence Livermore Laboratory (LLL) has been using a computer-controlled microdensitometer (XRPD) to make dimensional measurements on radiographs. The instrument was built to scan with a single round aperture. Previous studies of its performance indicated that, because of problems such as radiation scatter and electronic and film grain noise, its applicability was limited. To overcome some of these problems, the XRPD was modified by the installation of a mechanism that positions any

of five rectangular, as well as one round, apertures for scanning.

The performance of the instrument after modification was analyzed. In particular, the line-spread function and noise were measured for each aperture. An equation relating the XRPD output and film density was also derived for the operational domain of the instrument.

The results indicate that the XRPD performance—and its potential for use in the aerospace, weapons, and nuclear reactor industries—is improved as expected.

J. O. Hallquist, *NIKE2D: An Implicit, Finite-Element Code for Analyzing the Static and Dynamic Response of 2-D Solids*, Lawrence Livermore Laboratory, UCRL-52678 (1979).

This report provides a user's manual for NIKE2D and a brief description of the implicit algorithm. Sample applications are presented including the simulation of the necking of a uniaxial tension specimen, a static analysis of an O-ring, and a cylindrical bar impacting a rigid wall.

NIKE2D is an implicit, finite-deformation, large strain, finite-element code for analyzing the response of two-dimensional axisymmetric and plane strain solids. A variety of loading conditions can be handled including traction boundary conditions, displacement boundary conditions, concentrate nodal point loads, body force loads due to base accelerations, and body force loads due to spinning. Slide-lines with interface friction are available. Elastic, orthotropic, elastic-plastic, soil and crushable foam, thermoelastic-plastic, and linear viscoelastic material models are implemented. Nearly incompressible behavior that arises in plasticity problems and elasticity problems with Poisson's ratio approaching 0.5 is accounted for in the element formulation to preclude mesh lock-ups and the associated anomalous stress states. Variable node elements are used for the spatial discretization, and profile (bandwidth) minimization is optional.

C. A. Tatro, A. E. Brown, T. H. Freeman, and G. Yanes, *On-Line Safety Monitoring of a Large High Pressure High Temperature Autoclave*, Lawrence Livermore Laboratory, UCRL-81044 (1979). Prepared for ASTM Symp. on Acoustic Emission Monitoring of Pressurized Systems, Fort Lauderdale, FL, January 22-26, 1979.

Four years of experience with on-line monitoring of a large autoclave used primarily for forming bonds and material densification is reported. The purpose of this work is to confirm that no flaws are growing in the autoclave during operation. Failure of this device during operation could endanger personnel and would damage property. Its loss would seriously curtail several ongoing research efforts.

The vessel is monitored with a commercial minicomputerized flaw location system. Four 4-sensor arrays are attached to the exterior of the device to receive acoustic emission signals. Computed locations are stored on cassette tape and selected portions can be displayed on a cathode ray screen. It is shown that although the minicomputer is implemented with two dimensional location software, the information can be reprocessed in a central computer to produce locations in three dimensions.

Long term storage of data, data display, noise analysis, calibration, and computerized location error analysis is discussed.

No degradation by flaw growth has been detected in this device to date. This is the expected result, since it has an estimated 30-year life.

M. A. Gerhard and R. C. Greenlaw, *SLIC—An Interactive Mesh Generator for Finite Element and Finite Difference Application Programs*, Lawrence Livermore Laboratory, UCRL-81185 (1979). Prepared for Nonlinear Finite Element Analysis and ADINA Conf., August 1-3, 1979, MIT, Cambridge, MA.

Computers with extended memory, such as the CDC STAR 100 and the CRAY 1 with mega-word capacities, are greatly enlarging the size of finite element problems which we can solve. But the cost of developing and testing large meshes can be prohibitive unless one uses a computer program for mesh generation and plotting.

SLIC is an interactive mesh program which builds 2- and 3-D continuum meshes from interactive terminal or disc input. The user inputs coordinates for certain key points and enters commands which complete the description of the geometry. Entire surfaces and volumes are then generated from the geometric skeleton.

SLIC allows the user to correct input errors and saves the corrected command list for later reuse. The mesh can be plotted on a video display at

any stage of development to evaluate the work in progress. Output is in the form of an input file to a user selected computer code. Among the available output types are ADINA, SAP4, and NIKE2D.

W. S. Neef, Jr., and G. A. Carlson, *Mirror Fusion Reactor Design*, Lawrence Livermore Laboratory, UCRL-81908 (1979). Prepared for American Nuclear Society Meeting, Miami, FL, January 29-31, 1979.

Recent encouraging results in fusion physics experiments have again drawn attention to that most promising, but most elusive, means of nuclear power production. The toroidal devices called Tokamaks have received the largest share of research funding, and have reached some important milestones of density and temperature, while those fusion machines known as "mirrors" have also shown encouraging results. Both experiment and development of new theory have, in the past two years, brought "mirror" systems into a strong competitive position for consideration as future fusion power reactors.

R. C. Greenlaw and M. A. Gerhard, *Thermal-Stress Analysis of Rock Formations for Nuclear Fuel and Waste Storage*, Lawrence Livermore Laboratory, UCRL-81992 (1979). Prepared for Nonlinear Finite Element Analysis and ADINA Conf., August 1-3, 1979, MIT, Cambridge, MA.

ADINA and ADINAT in partnership have provided the Lawrence Livermore Laboratory with a unique tool for analysis of heat flow, temperature distribution, and underground stresses and deformations due to excavation and storage of nuclear fuel and/or waste canisters in hard rock formations.

During this work we have determined successful and unsuccessful combinations of elements and properties for both the thermal and the stress analyses. In addition, we have determined a need for thermal radiation transport between portions of the model, as contrasted to radiation between the model and its surroundings. This latter need has been met in the interim by use of non-linear bar conductors, and it will be satisfied in the future by a special user subroutine in ADINAT.

The geological modeling was preceded by a period of code testing and verification during which it was found that at least one material model did not

produce correct thermal stresses even though the thermal deformations were correct. We also found that thermal stresses were likely to be in apparent error due to differences in the way in which ADINA interpolates the temperature and strain fields within each element. Solutions to this problem are discussed.

J. B. Conner, *Leak Testing Requirements at a Research Facility*, Lawrence Livermore Laboratory, UCRL-82276 (1979). Prepared for Vacuum Technology Conf., Boston, MA, June 5 to 7, 1979.

Since September, 1952, Lawrence Livermore Laboratory has conducted pioneering research in applied science. A vital part of this activity has been the development of a variety of high vacuum and ultrahigh vacuum systems. Leaks occur in everything, including vacuum systems. The job of the mass spectrometer leak detection specialist is to determine an allowable leak rate for these systems and to insure that this rate is not exceeded.

Ronald D. Streit and Iain Finnie, *An Experimental Investigation of Crack-Path Directional Stability*, Lawrence Livermore Laboratory, UCRL-82308 (1979). Prepared for SESA 1979 Spring Meeting, San Francisco, CA, May 20-25, 1979.

Using the criterion that a crack will extend perpendicular to the maximum circumferential stress, we show that the directional stability of crack growth is governed by the location of micro-crack initiation ahead of the crack tip. At distances greater than a geometrical radius r_0 the maximum value of σ_θ deviates from the position of symmetry. Thus, if we assume that the physical processes involved in fracture lead to crack initiation at a distance r_c ahead of the crack tip, the criterion for directional stability is $r_0 > r_c$. Experimental and theoretical values of r_0 verify that as r_0 becomes small, the crack's directional stability deteriorates.

It was pointed out by Finnie and Saith that a lengthwise compressive stress increases r_0 and thus enhances directional stability. We have therefore, developed a center-cracked specimen which allows us to apply controlled lengthwise compression independently of the opening mode load. A detailed photoelastic analysis of the specimen has provided the value of r_0 as a function of the crack length. The

value of r_0 is then compared with the expected micro-crack initiation distances in ductile fracture.

In addition, by applying sufficient lengthwise compression, we are able to make the crack grow straight and obtain numerous data points from this specimen which would otherwise be directionally unstable. Further, we show that as the total lengthwise tensile stress at the crack tip increases, the fracture toughness also increases. Using this information we can then adjust K_{Ic} for zero A_2 loading and obtain a geometry independent fracture toughness.

T. A. Nelson, *Reserve Seismic Capacity Determination of a Nuclear Power Plant Braced Frame with Piping*, Lawrence Livermore Laboratory, UCRL-82423 (1979). Prepared for the 5th International Conf. on Structural Mechanics in Reactor Technology, Berlin, Germany, August 13-17, 1979.

(See UCRL-50916-79-1 for details.)

C. K. Chou, T. Lo, and V. Vagliente, *Major Structural Response Methods Used in the Seismic Safety Margins Research Program*, Lawrence Livermore Laboratory, UCRL-82439 (1979). Prepared for the 5th International Conf. on Structural Mechanics in Reactor Technology, Berlin, Germany, August 13-17, 1979.

In order to evaluate the conservatism in present nuclear power plant seismic safety requirements, a probabilistic based systems model is being developed. This model will also be used to develop improved requirements. In Phase I of the Seismic Safety Margins Research Program (SSMRP), this methodology will be developed for a specific nuclear power plant and used to perform probabilistic sensitivity studies to gain engineering insights into seismic safety requirements.

J. W. Pearson, *Precision Machining vs Optical Process*, Lawrence Livermore Laboratory, UCRL-82528 (1979). Prepared for SIRA-NPL Conference on Advances in Optical Production Technology Teddington, Middlesex, England, April 24-25, 1979.

High multiples of advantage in both time and cost make the emerging technology of advanced precision machining attractive as a fabrication

process for a class of optical parts. The capability of the numerical control machine tool to cut complex geometries allows functional design improvements of optical elements over what is economically feasible by conventional optical process. Machining optical parts, however, is limited to materials amenable to the diamond tool bit, which excludes glass and ferrous metals, but includes ductile metals, plastics and a number of other materials suitable for optical elements.

J. B. Bryan, *The Abbe' Principle Revisited—An updated Interpretation*, Lawrence Livermore Laboratory, UCRL-82591 (1979). Prepared for Precision Engineering.

The Abbe' principle was first made public in a paper published by Prof. Abbe' in the Journal for Instrumental Information, Vol. X, 1890. In this paper Prof. Abbe' discussed the benefits of using divided scales as length measuring systems. He also discussed the benefits of arranging the measuring scale to be in line with the distance to be measured.

L. L. George, *Optimal Opportunistic Engine Build Policies*, Lawrence Livermore Laboratory, UCRL-82607 (1979). Prepared for 14th Annual SOLE Symp., Society of Logistic Engineers, Clearwater, FL, August 12-16, 1979.

Opportunistic maintenance consists of opportunistic replacement policies and opportunistic build policies. Replacement policies specify which parts to remove when an opportunity arises. Build policies specify which parts should be taken from the spares inventory to replace the parts removed according to the opportunistic replacement policies. Both policies should be used to reduce future maintenance requirements.

The objective of opportunistic build policies is to build engines with age compatible parts. This objective is measured by the number of future scheduled removals or the removal rate. If the spare parts are functionally identical but otherwise unequal, careful selection of the parts to install can reduce future engine removals.

This paper describes single and multiple engine opportunistic build policies for engines with repairable or nonrepairable parts. The problem of determining optimal opportunistic build policies is combinatorially difficult. An approximate solution

method can be applied to opportunistic build problems, and the method is guaranteed to give close to an optimum solution for engines with two life limited parts.

J. D. Lee, *The Beryllium/Molten Salt Blanket—A New Blanket Concept*, Lawrence Livermore Laboratory, UCRL-82663 (1979). Prepared for the Third US/USSR Symp. on Fusion-Fission, Princeton, NJ, January 22-26, 1979.

The Beryllium/Molten Salt (Be/MS) blanket is an interesting contender for fissile breeding fusion reactors. Beryllium is used for neutron multiplication, and a Li and Th containing molten salt is used for on line removal of bred fusile (T) and fissile (U233) fuels. A conceptual Be/MS blanket has unique characteristics that may be advantageous and their potential advantages are presented.

It is hoped that this presentation will stimulate further study on the Be/MS blanket concept.

D. H. Chung, *Parametric Studies of Physical Conditions in the Earth's Upper Mantle*, Lawrence Livermore Laboratory, UCRL-82670 (1979). Prepared for Tectonophysics.

Seismic body-wave and surface-wave data indicate the existence of a substantial low-velocity, low-Q zone in the upper mantle beneath western North America. Conditions in this zone are distinctively different from those that are typical of the upper mantle in shield regions. The present study, using Walsh's model for partially melted rock, suggests a common mechanism for low-velocity and low-Q zones. This parametric study also indicates that the low-velocity, low-Q zone and anomalous travel-time delays of both P and S waves in the Basin and Range Province are consistent with the combined effects of high temperature, chemical composition, phase changes, and partial melting. The observed low P_n velocity in this region is consistent with high temperature, chemical composition, and the presence of a partially molten layer within the upper mantle, but the observed teleseismic delay times result principally from the thickness of the low-velocity zone. The teleseismic delay-time variations are therefore related to the seismic Q distribution in the asthenosphere. Conditions a few kilometers beneath the Moho boundary influence the P_n velocity; however, the observed correlation

among the teleseismic signal amplitudes, travel-time delays, and the upper mantle Q indicates that the P_n velocity is a better indicator of upper mantle Q than suggested by the P_n path alone. This knowledge of the upper mantle seems to account for the anomalous effects of the Basin and Range Province and other regions of similar tectonic nature on observations of teleseismic events. This will provide a practical technique for comparing seismic observations made in unstable tectonic regions with observations made in shield areas.

M. W. Schwartz, *The Effect of Mechanical Energy Storage Systems on the Characteristics of Electric Vehicles*, Lawrence Livermore Laboratory, UCRL-82710 (1979). Prepared for the American Chemical Society 14th IECEC Meeting, Boston, MA, August 5-10, 1979.

Batteries for electric vehicle propulsion can be developed to effect trade-offs between short-term peak power capability and energy storage capacity. Such batteries in combination with a mechanical energy storage device can optimize both power and range capability of an electric vehicle. Equations are derived for determining the vehicle mass fraction of the mechanical energy storage system that is required to achieve a vehicle mass saving or increase in range. The extent to which mechanical energy storage systems can improve electric vehicle performance depends upon the battery type and the vehicle power/mass requirements.

J. Fink, *Value Engineering and the Role of R & D in the Neutral Beam Program*, Lawrence Livermore Laboratory, UCRL-82712 (1979). Prepared for Value Engineering Workshop, DOE—German-town, MD., April 4 and 5, 1979.

Value Engineering, simply defined, is a systematic approach to getting more for your money. It has been used to reduce the cost of a wide variety of products by the D.O.D. and in principle, should be applicable to various phases of the Neutral Beam Program. With respect to R & D, the principles of Value Engineering must be used with caution. They are most effective in evaluating directed development with very specific goals, but can be misleading when considering advanced innovative work.

W. H. McMaster, *Eulerian Fluid-Structure Analysis of BWR*, Lawrence Livermore Laboratory, UCRL-82735 (1979). Prepared for 1st Intern. Seminar on: Fluid-Structure Interaction in 'LWR' Systems, West Berlin, Germany, August 20-21, 1979.

We have developed a fluid-structure-interaction algorithm for the analysis of the dynamic response of a BWR pressure-suppression pool and containment structure. The method is incorporated into a two-dimensional semi-implicit Eulerian hydrodynamics code, PELE-IC, for the solution of incompressible flow coupled to flexible structures. The fluid, structure, and coupling algorithms have been verified by calculation of solved problems from the literature and by comparison with air and steam blowdown experiments.

The solution method for the fluid motion is based on the SOLA algorithm which uses a Newton Raphson iteration on the fluid pressure field to solve the mass conservation equation for incompressible fluids. For the applications to BWR, we have developed two new algorithms to treat the boundary conditions at free surfaces and fluid-structure interfaces. These algorithms are general in nature and are capable of treating a wide variety of structural shapes.

The structural motion is computed by a finite element code from the applied pressure at the fluid-structure interface. The shell structure algorithm uses conventional thin-shell theory with transverse shear. The finite element spacial discretization employs piecewise-linear interpolation functions and one-point quadrature applied to conical frustra. We use the Newmark implicit time integration method implemented as a one-step module.

The fluids code then uses the structure's position and velocity as boundary conditions. The fluid pressure field and the structure's response are corrected iteratively during each time step until the normal velocities of the fluid and the structure are equal. This results in a strong coupling between the two algorithms.

C. S. Landrum, *Vessel Discharge by Friction Dominated Tube Flow*, Lawrence Livermore Laboratory, UCRL-82801 (1979). Prepared for the Gas Dynamics Conf., Sandia Laboratories, Livermore, May 22-23, 1979.

The analytical complexities associated with predicting the discharge of a contained gas from its vessel through a long isothermal tube are simplified. The choking and unchoking temporal regions are shown to be dependent upon the form taken for friction factor, and the solution is therefore shown

to depend rather intimately on such forms. Measured and calculated vessel pressure histories are favorably compared for the case of an ideal gas (He) discharging to the atmosphere in laminar flow through a tube of length to diameter ratio 1.2×10^4 .