Mechanical Engineering Department Technical Review

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PREFACE

The Mechanical Engineering Department Technical Review is published to inform readers of various technical activities within the Department, promote exchange of ideas, and give credit to personnel who are achieving the results.

The report is in two parts: technical achievements and publication abstracts. The first is divided into seven sections, one for each division in the Department.

These technical achievement articles are summaries of ME work. For additional details on a subject, please contact the individual(s) listed at the end of each article. Inasmuch as most projects are the result of cooperative efforts, the article contact may refer you to another individual who can best answer your question.

The second part of the biannual Technical Review contains the titles or abstracts of laboratory reports published by Mechanical Engineering personnel since the previous issue.

The ME Technical Review Committee members include:

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NUCLEAR TEST ENGINEERING DIVISION

The Nuclear Test Engineering Division (NTED) provides mechanical engineering and technical expertise to prepare and field nuclear tests and to conduct analytical and experimental studies involving nuclear safety in general and seismic response of reactors in particular. In addition, we support numerous Laboratory energy programs and the Earth Sciences (K) Division experimental work. The NTED also provides mechanical engineering services for spill effects testing at China Lake and NTS under the Liquefied Gaseous Fuels Program.

Nuclear Testing

Our nuclear testing activities and responsibilities involve the design, structural evaluation, fabrication, and proof testing of diagnostic and device canisters that position radiation detectors and protect nuclear explosives in an underground environment. We emphasize efforts to improve data quality and field operations, optimize cost effectiveness, and maximize safety. We synthesize, procure, and certify the arming and firing systems. The underground diagnostic systems that we provide require development and fielding of downhole emplacement systems. We develop containment systems to meet zero detectable radioactivity release requirements. In addition, our advanced development projects include new diagnostic techniques and field engineering concepts designed to optimize 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). We are responsible for providing sound technical data on which NRC can base licensing decisions and assessment tools to protect public health and safety. In this multidisciplinary effort over the past 6 years we have been engaged in more than 60 separate NRC reimbursable contracts. In our work most of the

facilities of the nuclear fuel cycle have been considered from the structural integrity viewpoint, including fuel processing and fabrication, accident analysis (particularly containment systems), 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.

A general goal we have is to establish LLNL as a national and international center of seismic excellence. We are currently NRC's lead laboratory concerning seismic safety.

Energy Programs

We provide mechanical engineering support to many of the Laboratory's smaller energy programs and to a number of scientific projects in the earth sciences fields. Some of our current efforts include work in solar thermal, solar fuels, oil shale, geothermal, underground coal gasification, radionuclide migration, spent reactor fuel storage, and geophysics research. We have responsibility for designing, building, and operating both laboratory experiments and off-site field engineering tests.

Dynamic Response of Epoxy Plugs in Nuclear Test Emplacement Holes

During preparation for several events in 1979, high diagnostic cable loading was observed in the stemming operation, inferring that the upper coal tar epoxy (CTE) plugs had moved. On another event, Norbo, the upper CTE plug moved after the event. This movement was later determined to have occurred because of poor plug adhesion to the surface conductor wall.

As a consequence of these suspected CTE plug movements, plug measurements were performed on three 1980 events—Colwick, Kash, and Tafi—on Pahute Mesa at the Nevada Test Site. We chose these events to provide full-size measurements for relatively large ground motions in order to induce maximum input loads into the upper CTE plug in the surface conductor. The expanded experiments included stemming and plug measurements during the stemming operation and continuing through

shot time. The overall configuration of these experiments is shown in Fig. 1. Numbers in parentheses in this text refer to specific locations as shown on the figure.

Static (before the event) and dynamic (during the event) plug displacement near the center and wall of the plug were measured with stiff rods (pipes) extending to the surface (55, 56). Static displacements of the bottom part of the plug (53, 54) and the stemming just below the plug (51, 52) were measured relative to the emplacement pipe. Emplacement pipe strain (83) and dynamic displacement (84) were also measured. Acceleration and velocities were measured in the plug (21) and in the ground near the surface (61). The acceleration of the surface conductor was measured at two locations 180 deg apart (62, 63).

The stemming and plug displacement gauges (51-56) were released and displacement data were recorded at the earliest possible time to ensure that we measured their full history. The stemming displacement gauges (51, 52) were released before the rigid CTE plug was poured. Immediately after the plug pour, the displacement gauges (53-56) in the plug were released. At this time the plugs had not cured, but the gauges were supported by the gravel used as filler in the CTE plug.

Measured results from all three events showed good agreement. The following Colwick results are typical:

- Upon release, there is a 0.1-to-0.2-in. settlement of the stemming displacement gauges [Fig. 2(a)]. After the CTE plug pour, the stemming compacts 0.2 to 0.4 in. During the next 3 to 7 hr, 0.1 in. additional displacement occurs.
- The gauges in the lower part of the plug settle 0.2 in. upon release [Fig. 2(b)] and then settle out with an additional displacement of 0.1 in. within 8 hr.
- The upper p. g displacement rods settle 0.4 in. into the uncured CTE plug upon release [Fig. 2(c)] because of their heavy weight. An additional displacement of 0.1 in. occurs within 8 hr. After 8 hr. all displacement transducers remain constant until shot-induced motion occurs.

After zero time, the first motion observed at Surface Ground Zero (SGZ) is when the emplacement pipe moves upward. When the ground shock compressive wave passes the stemming under the plug, the stemming consolidates and is no longer in contact with the bottom of the plug. As the upper

layer of ground, including surface conductor and CTE plug, falls back it impacts a lower layer of ground. At this time, the plug dynamic displacement averaged 0.3 in. during the Colwick Event [Fig. 2(c)]. The plugs then return to their original position. A series of horizontal bands, each 2-in. wide and painted at the top of each plug displacement rod, provided mechanical verification that the plugs were not permanently displaced during the event.

The SGZ ground motions on all three events were within the predicted ranges. Peak positive velocities were 5.1 to 7.4 m/s, with peak negative velocities from 7.4 to 8 m/s. Peak accelerations in the ground were 5.3 to 7 g initial and 12 to 36 g impact at spall closure. Peak accelerations in the surface conductor and rigid plug were lower than those in the ground: 4.6 to 6.2 g initial and 4.6 to 18 g at impact.

The impact energy involved in these experiments was up to 326 times the impact energy experienced on the Norho Event, which verifies that properly installed CTE plugs remain in position under severe dynamic conditions.

For further information, contact F.C. Jackson, Ext. 2-8480

Atlas Trailer Shock Isolation System Conversion Nears Completion

Nuclear test information and data are conditioned or recorded on electronic equipment. This relatively fragile equipment is housed in trailers and must survive the severe three-dimensional ground motion induced by the underground nuclear explosion.

Before the NTFD was formed, equipment was damaged and some trailers even tipped over. Many years ago we developed several trailer shock isolation systems that have proved to be reliable and have allowed documented net savings of approximately one million dollars per year. When properly installed, these systems have withstood 13-ft vertical ground upheaval; however, the installation was labor-intensive. In 1977 we designed a new system to accommodate a more efficient method of providing shock absorption—the Atlas Trailer Shock Isolation (ATSI) system. The ATSI design was based on our previous successful designs, but it required a one-time retrofit to each trailer structure.

FIG. 1. Schematic showing location of instrumentation used to measure the static and dynamic movement of the CTE plug in the surface conductor throughout its installation and during the event.

FIG. 2. Measured displacements in the CTE plug and the stemming immediately beneath it for the Colwick Event.

The new system reinforces the trailer structure and allows it to accept interchangeable standard support modules. In all cases, the road gear suspension system remains on the trailer. Structural modifications to the trailer include: (1) transverse rails to increase the trailer structural strength and guide the interchangeable modules into place; (2) reinforcement cross beams as required; (3) reinforcement along the length of the trailer; and (4) a standard attaching bolt-hole pattern.

When the diagnostic trailer arrives at the trailer park, it is placed in proper location on its landing legs. The modules (395 lb each) are unloaded with a hydrocrane and immediately slid halfway into position on the trailer. The crane is unhooked, the module is pushed all the way in, and two bolts are installed. For relatively low ground motion, the module is installed in its straight (S) mode and a rigid foam pad is bolted on underneath, as shown in Fig. 3(a). To withstand severe ground motion, the module is installed in the column (C) mode depicted in Fig. 3(b). For the C mode, the final assembly steps are: (1) position a low-friction foot pad and plywood spacer disks; (2) insert a column from above through the module and into the foot pad where the column is retained by spring clips; (3)

raise the trailer approximately 4.5 ft; (4) insert foam crush pads and wrap with filament tape; and (5) lower the trailer onto the crush pads.

Because of heavy event schedules for the trailers, their availability for the conversion work was a major problem. Although each retrofit took only about a month at our EG&G North Las Vegas facility, we had to phase the work over a 3-yr period. However, all but two of the 35 adaptable trailers have now been converted to the ATSI system. With the new system, we have experienced more than a 50% savings in man-hours per trailer per event, and have increased overall reliability with a reduced quality assurance effort. Man-hour savings per trailer for high-yield shots average 110, and for low-yield shots, 30 man-hours. We estimate that the ATSI system decreased the operational costs of shock-mounting trailers by approximately \$200,000 for calendar year 1980.

One of the converted shock-mounted trailers is shown in Fig. 4.

(For further information, contact E.C. Jackson, Ext. 2-8480.)

FIG. 3. (a) Small vertical displacement configuration, and (b) large vertical displacement configuration of the Atlas Trailer Shock Isolation (ATSI) system trailer conversions.

FIG. 4. ATSI-configured trailer in C mode (large vertical displacement). In this mode, the trailer may slide horizontally several feet; movement is arrested by nylon tether lines. Shown on the left is the entrance platform with articulated steps for personnel safety during postshot entry to the trailer.

A Concept for Underground Nuclear Power Plant Siting to Retain Postaccident Atmospheres

Preliminary design criteria developed for a general case 1100-MWe power plant show that underground siting of nuclear power reactors is practicable and safe.^{1,2} The concept calls for open-pit excavation in any geological medium to allow construction of the reactor containment structure (Fig. 5). A desirable depth of excavation for the containment building and steam generators is about 90 m. After construction the pit is backfilled with selected earth material as shown in Fig. 6. The backfill is designed so that it will confine, within a small envelope, any radioactivity release that might result from a rupture of the containment structure. To complement this "natural" barrier to release of radioactivity, techniques for effective closure of the large system pipes (Fig. 7) and for cable gas blocking (Fig. 8) are applied from experience gained in underground nuclear device testing. The additional cost of putting the nuclear portion of the system underground is only a small fraction of the cost of a conventional, surface nuclear power plant. Location of the turbine generator sets underground

represents an unnecessary additional excavation cost so it is recommended that they be located at or near the surface. Underground reactor siting (as proposed herein) will apparently require no new technology.

The results of this study should still be regarded as preliminary in demonstrating that underground siting is a viable alternative to present practice for nuclear reactor power plants. It shows, however, that underground installation can be accomplished with existing technology, much of which has been developed from extensive analytical, experimental, and field experience on the underground containment of nuclear device testing.

If the conclusions are supported and the underground reactor becomes a viable alternative, overall plant construction time could be materially reduced by shortening the time from plant proposal to receipt of construction permit. This time savings would result from simpler (faster) review for licensing, made possible by the increased inherent safety.

As a result of this initial study, the following conclusions are drawn:

1. By siting large power reactors underground in suitably backfilled excavations,

FIG. 5. A concept for underground siting of nuclear power reactors.

FIG. 6. Zoning for low-permeability backfill design.

FIG. 7. Typical high pressure gas-operated valve.

FIG. 8. The cable gas block.

harmful radiation from the worst-case possible accident can be confined.

2. Underground siting in the manner proposed applies to any type of light water reactor.

3. The additional costs of underground siting are negligible. In fact, shortened construction times due to reduced environmental-impact effects can be expected, with consequent cost savings.

4. Closure technology developed for containment of underground nuclear tests is directly applicable to underground siting of reactors.

**For further information, contact B.R. Bowman, Ext. 2-0325, H.F. Bailing, Ext. 2-9253, or E.W. McCutchen, Ext. 2-6974.*

Processing Techniques for Data from the GKSS Pressure-Suppression Experiments

This summary outlines the techniques developed at the LLNL for processing data from large-scale steam-condensation experiments being performed by the GKSS* Research Center in the Federal Republic of Germany. In particular the computer code GKPLOT, a special evaluation program for generating time-history plots and numerical output files of GKSS data, has been developed, together with tape handling techniques required to unblock the data to a form compatible with the LLNL Octopus computer network. Using these data processing techniques, we have provided a convenient means of independently examining and analyzing a very extensive data base for steam-condensation phenomena. In addition, the techniques developed for handling the GKSS data are applicable to the treatment of similar, but perhaps differently structured, experimental data sets.

The GKSS Research Center (Geesthacht-Tesperhude, Federal Republic of Germany) is currently engaged in a research program concerning the response of a boiling water reactor (BWR) pressure-suppression system (PSS) to the late-time steam-condensation phase of a postulated loss-of-coolant accident (LOCA).³ Such systems are an integral part of an overall BWR safety program, both

in West Germany and in the United States. The Lawrence Livermore National Laboratory (LLNL) has been designated by the U.S. Nuclear Regulatory Commission (U.S. NRC) as its principal liaison for this test program. Particular emphasis is placed on developing confirmatory data to assess the containment performance of General Electric Mark II nuclear power plants in the U.S., and to develop a comprehensive research data base for advanced code validation and further understanding of steam-condensation phenomena. The multivent GKSS test facility (Fig. 9), which was placed in operation in February 1979, provides a full-scale, three-vent pipe system that models the basic features of both the West German Kraftwerk Union (KWU) and the Type 69 United States GE Mark II pressure-suppression systems. The time-correlated measurements system⁴ consists of one hundred twenty-eight 100-Hz and fifty-six 1.7-kHz digital-data acquisition channels, and six 40-kHz analog channels. Visual data is also collected by three 50-Hz television cameras which view both the water surface and the vent pipe outlets, and a high speed (1000 frames/s) 16-mm camera which views one vent exit.

The range of parameters treated by this extensive instrumentation system is broad. Primary emphasis is placed on the measurement of pressure and temperature throughout the facility, although other parameters such as water level, force, strain, and acceleration are also studied.

As part of its liaison activities with GKSS, LLNL routinely receives magnetic computer tapes containing digital data* recorded for each test in the research program. Management of GKSS data at LLNL is undertaken in three successive steps:

- Unblocking of the original data tapes supplied by GKSS into a single packed-ASCII format disk file compatible with the LTSS (Livermore Time-Sharing System).
- Redistribution of the data among several smaller disk files to enhance data manageability.
- Accessing the data (interactively or automatically) to generate time-history plots, or to generate numerical input for subsequent data analysis (e.g., frequency analyses). A typical time-history plot is shown in Fig. 10.

*Gesellschaft für Kernenergieverwertung in Schiffbau und Schifffahrt GmbH (Company for the Utilization of Nuclear Energy in Ship Construction and Navigation).

*Consisting of about 40 000 data points per channel of 100-Hz data and about 720 000 data points per channel of high speed data.

FIG. 9. The GKSS multivalent pressure-suppression test facility.

FIG. 10. Overlay pressure-time history plot.

The first two steps are only performed once for each data set, resulting in standard sets of input files for the LLNL data access software. Thus, under normal circumstances the original data tapes from GKSS are handled only once.

(For further information, contact E.W. McCauley, Ext. 2994.)

Evaluation of the Seismic Integrity of a Plutonium Handling Facility

Many studies⁵⁻¹² have been made by and for the Lawrence Livermore National Laboratory (LLNL) to ensure the seismic safety of its Plutonium Facility (Building 332). These studies have included seismologic and geologic field investigations to define the actual seismic hazard existing at the Laboratory site as well as structural studies of the Facility itself. Because the basic

seismic design criteria have undergone changes over the years, numerous structural studies and upgrades have been completed. The seismic criteria in use at the LLNL site is reviewed on a continuing basis as new information on the seismicity and geology of the Livermore Valley is obtained. At present, the Laboratory's Earth Sciences Division is conducting a multimillion dollar program to identify and characterize the geologic hazards at the Livermore site, with the primary emphasis on earthquake hazards in the Livermore Valley. This effort is undergoing an independent review by Woodward-Clyde Associates of San Francisco, Calif. Additionally, because of increased concerns over the seismic safety of Building 332, the Laboratory has initiated an independent structural review. This effort will be monitored by the California Seismic Safety Commission (CSSC) to ensure independence of the review. Both of these studies are in their early stages and results are not yet available.

Plutonium Facility Description

The Laboratory's Plutonium Facility was built expressly for handling plutonium. In plan view it looks like two buildings with a narrow connection between them (see Fig. 11). Plutonium is handled only in the Facility's radioactive materials area, Increments 1 and 3. Increment 1 includes offices, a mechanical-equipment room, dressing rooms, plutonium laboratories, and a loft that houses the ventilation system. Increment 3 includes the corridor and air lock, a small control room, the main plutonium storage vault, four large laboratories, and a basement that houses mechanical equipment, the ventilation system, and emergency power and water supplies. Increment 2 is a minor addition in the corner where the connecting Increment 3 structure meets Increment 1. The plutonium handling areas are reinforced concrete, shear-wall construction.

Functionally, the design of the Facility is based on erecting multiple barriers to the propagation of fires and to the formation and release of plutonium particulates. These barriers are gloveboxes, the ventilation system, and the structure of the building itself.

These barriers, together with the safety measures adopted in operating the building, constitute the protection LLNL provides both to Laboratory employees and to the public against the potential hazards of plutonium.

Seismic Design Basis

The Plutonium Facility, Increment 1, completed in 1961, was designed and built in accordance with the Uniform Building Code. After the San Fernando, California, earthquake of February 1971, LLNL examined in detail the seismic hazard for the Laboratory site.⁵ An independent engineering and geology firm was engaged to carry out both a seismologic and geologic field investigation of the area.^{6,7} From this investigation, it was concluded that the maximum ground motion at the site would be a horizontal acceleration of 0.5g with no evidence of a potential for surface offset near the Plutonium Facility. This 0.5-g maximum horizontal acceleration and a response spectrum were established as the design-basis earthquake* for the

*The design-basis earthquake for a site is defined as the earthquake that will produce the maximum possible ground motion at the site, after which structures, systems, and components important to safety associated with facilities that house radioactive materials must remain functional.

FIG. 11. Plan view of Building 332 (ground floor). The radioactive materials areas are shaded.

Livermore site. After a detailed review of the 1972 study, LLNL's staff in 1974 derived a value of 0.8g for the maximum horizontal acceleration of the ground due to earthquake shaking.¹² In light of this result, the LLNL staff is using this higher ground motion value to reevaluate all Laboratory facilities that house radioactive material at the Livermore site.

Structural Studies and Upgrading

Because of changing seismic design criteria over the years, numerous structural studies and upgrading have been completed. In 1973, LLNL initiated a Laboratory-wide program to secure gloveboxes, equipment, and systems against shaking caused by earthquakes. Throughout the Laboratory, all such items that needed to be tied down were secured against a seismic loading equivalent to a 2.0-g horizontal acceleration. The Laboratory also did some confirmatory experimental investigations into the integrity of gloveboxes. In these experiments, the glovebox, the filter, and the tools inside were subjected to a ground shock level

of 1.0 g. Results from these tests and other analyses by LLNL staff clearly indicate that gloveboxes like those in the Plutonium Facility will easily survive earthquake ground motions at the 1.0 g level without damage.

Currently, LLNL is in the process of reevaluating facilities that house appreciable amounts of radioactive material at the Livermore site for a peak ground acceleration of 0.8 g. Because of public attention centered on the Plutonium Facility, this reevaluation concentrates on the as-built structures of Increments 1 and 3 of Building 332. As part of this reevaluation, the LLNL staff has already assessed the integrity of this facility to the 0.8 g level. Our results show no significant structural problems are anticipated.

The recent controversy surrounding the Las Positas fault zone to the south of the LLNL site, as mapped by the USGS in 1977, does not adversely affect the seismic analysis results and conclusion. The potential ground motion levels are not increased, and no evidence of a potential for surface offset near the Plutonium Facility has been found.

In the interest of promoting a consensus concerning the seismic hazard at the Livermore site, LLNL has recently initiated comprehensive field investigations. We are also initiating independent structural evaluations. Both studies will use outside private industry reviewers.

Independent Review of LLNL Plutonium Facility

Because of increased attention focused on the seismic safety of the Plutonium Facility following the Greenville earthquake sequence of January 1980, LLNL and the Department of Energy, San Francisco Operations Office (DOE SAN), have initiated an independent structural review. The objective of this review is to provide an independent assessment of the expected performance of the Building 332 structure, systems, and components under earthquake-generated ground accelerations.

To help ensure the independence of the review process, the CSSC has agreed to review all phases of the procedure, from the selection of the review team to the production of a final report and public meeting to present the findings of the panel.

As of this writing the selection of qualified independent reviewers is in the initial stage. The primary criteria used to select potential reviewers were as follows:

- Must have broad experience in seismic structural dynamics and structural engineering.
- Must be familiar with the characteristics of California earthquakes.
- Must have experience in observation of structural damage caused by earthquakes.
- Must command peer recognition for their work in seismic engineering and public respect based on their professional achievements.
- Must be practicing in the field of seismic engineering, preferably experienced in addressing the dynamic behavior of structures similar to Building 332, such that their familiarity with the issues is current and based on experience.
- Authority to use the title "Structural Engineer" is highly desirable. All reviewers under consideration have met the approval of the CSSC. A minimum of three reviewers will make up the review team. At the conclusion of the review process, the review team will submit a joint draft final report to the DOE SAN office. This report will then be made available to the CSSC and the public in preparation for a public discussion of the review team findings.

After the public meeting, the review team will address relevant public comments and any comments or observations offered by the CSSC. A final report signed by all reviewers will be delivered to the DOE.

Conclusions

The LLNL has completed extensive investigations and studies to ensure the seismic integrity of Building 332. This work has included both defining a design-basis earthquake for the site and making structural analyses to evaluate the integrity of the built-in safeguard barriers—i.e., the building, the gloveboxes, and the ventilation system. Additionally, studies are currently under way to further identify and characterize the seismology and geology of the Livermore Valley and to perform an independent, structural assessment of Building 332.

(For further information, contact D.W. Conry, Jr., Ext. 2-0307.)

Dynamic Seismic Analysis of Unit 4 of the El Centro Steam Plant

On October 15, 1979, at 4:16:55 p.m. (PDT) an earthquake that had a Richter magnitude M_L of 6.6 shook California's Imperial Valley. The epicenter was on the Imperial Fault, 5 km southeast of the El Centro Steam Plant. There was no loss of life in this sparsely populated agricultural area, but there was some property damage and extensive damage to irrigation facilities.

When the earthquake occurred, only units 3 and 4 of the four-unit nonnuclear El Centro Steam Plant were operating. The operating units tripped off line when station power was lost because of a short circuit. Units 3 and 4 were restored to service within 2 hr.

There was some minor damage to the facility; however, the two operating units safely shut down with no known malfunctions of electrical control and instrumentation equipment during or after the earthquake.^{13,14}

At the request of the U.S. Nuclear Regulatory Commission, the Lawrence Livermore National Laboratory (LLNL) performed a dynamic seismic analysis of Unit 4 of the El Centro Steam Plant to analytically estimate structural and equipment response. Built in 1968, the oil-fired Unit 4 was designed to resist a static lateral force equivalent to 20% of the dead and live load. The unit's structural and mechanical systems sustained only minor damage during the earthquake, which produced an estimated 0.5 g peak horizontal ground acceleration (0.66 g vertical) at the site. This earthquake level, it should be noted, is larger than almost all safe shutdown earthquakes (0.2 g) used for the design of nuclear power plants. Figure 12 is a photograph of the plant.

Structural Model

The seismic response of the turbine building and its associated structures was determined using a normal mode, time-history method of analysis with a linear elastic model composed of equivalent vertical beam members with masses lumped at floor

FIG. 12. View toward the south side of Unit 4 of the El Centro Steam Plant.

FIG. 13. Lumped-mass and beam model of Unit 4. Note the separate turbine pedestal beam, the translational and rotational soil springs, and the different locations at certain elevations of centers of gravity and rigidity.

levels. A schematic representation of the analysis model is shown in Fig. 13. Each model mass point represents the mass of the floor, boiler, and equipment at the respective level and a proportionate share of the mass of the walls and columns between each level. All masses are lumped at the respective

floor levels of the structure. Each mass point has six degrees of freedom. The turbine building and the boiler support tower structural steel are interconnected and monolithically cast within concrete shear walls.

The material damping is taken as 10% of critical damping for the concrete portions and 7% for the steel portions—the value recommended for highly stressed elements in NUREG/CR-0098.¹⁵ Note that the structure as a whole was not damaged; however, the use of these high damping values will lead to a low estimate of the equipment acceleration and, by implication, its capacity.

Soil-Structure Interaction

To account for soil-structure interaction, the soil was treated as an elastic half-space, and soil springs and damping were developed using the formulations in Ref. 16. The resulting six springs—three translational and three rotational—were attached to the center of rigidity at the midplane of the base slab.

In performing soil-structure interactional analyses, the large calculated damping ratios for the soil are frequently of concern. This is especially true when using modal superposition methods with frequency-independent soil parameters. As indicated in Ref. 17, when the soil damping gets very high the response approaches that of the fixed-base case.

For this analysis, the responses of the centers of gravity of the base mat and operating floor were compared for the fixed-base case and the flexible-base case, which uses composite modal damping incorporating the high damping ratios calculated.

Parameter studies were conducted using an arbitrary 40% cutoff on composite modal damping. Based on these studies, it was decided that the calculated values were reasonable except in the case of damping for the vertical direction where logic constraints of the software necessitated a maximum input value of 100% damping.

Seismic Input

The time-history input was obtained from records of the October 15, 1979, Imperial Valley earthquake recorded at U.S. Geological Survey Station No. 5165.¹⁸ Since the three components of the records were properly timed-phased, all three were simultaneously applied in the analysis. A ground motion of 20 s with a 0.01-s time step was used for this analysis.

Peak Acceleration and Response

The maximum accelerations and response for the main equipment floors are shown in Table 1. Note that the floor accelerations in the turbine building decrease as elevation increases. This behavior results from the soil springs, which cause an increase in the participation of higher modes compared to the fixed-base analysis.

The maximum predicted base shear values are relatively close to the design base shears determined from Ref. 19.

To estimate equipment response, in-structure response spectra nodes were selected and considered to be rigidly attached to the center of rigidity at each elevation in the model. Acceleration time histories and response spectra were generated at each node. Then, for each direction, fundamental frequency and damping ratios were estimated for each of the 41 equipment items considered. The frequencies were either calculated, estimated by engineering judgment, or estimated by comparison to similar equipment for which frequencies were determined by analysis or test. Damping values were estimated for elastic response. Equipment acceleration responses were determined from the various in-structure response spectra. In general, the equipment acceleration responses varied from 0.5 to 1.8 g in the N-S direction, 0.4 in the E-W direction, and 0.4 to 1.55 g in the vertical direction.

Conclusions

We concluded that the turbine building dynamic model with highly damped soil springs reasonably reflects the forces induced in the building during the earthquake. This conclusion is evidenced by the following:

- The low level of damage observed at the plant.
- The close relationship of the design to predicted base shears.
- The low displacement at the turbine pedestal.

In drawing conclusions about structural response, it is difficult to relate the static loading design criterion (a static lateral load equivalent to 20% of the dead as well as the live load) to an earthquake loading characterized by a particular peak ground acceleration. However, for this particular earthquake and structure the triaxial time history gives base shear values in close agreement with the original design values.

TABLE 1. Maximum structural accelerations for main equipment floors in units of g.

Elevation (ft)	Peak ground acceleration		
	0.49 (N-S)	0.35	0.66 (vertical)
Turbine building			
998.7	0.51	0.37	0.36
983.0	0.51	0.38	0.37
969.0	0.52	0.39	0.39
949.0	0.55	0.40	0.40
Turbine pedestal			
969.0	0.52	0.38	0.39

The forces experienced by the plant equipment were on the order of 2 to 9 times greater than the 0.2 g specified design load. This would seem to imply a reserve seismic equipment capacity of about 200%. However, it is difficult to verify this value without knowing the actual lateral load the equipment could withstand. One can only conclude that nuclear power plant equipment similar to that in Unit 4 and anchored as well should perform equally well during a similar earthquake.

(For further information, contact R.C. Murray, Ext. 2-0308, or T.A. Nelson, Ext. 2-0306.)

Development of Probabilistic Seismic Failure Relationships of Nuclear Components for the SSMRP

The Seismic Safety Margins Research Program (SSMRP)²⁰ is an NRC-funded multiyear program directed toward estimating the conservatism in the current NRC seismic safety requirements with the ultimate goal of developing improved seismic requirements. As part of this program, calculations are being made of the risk of radioactive release from a typical commercial nuclear reactor in the event of earthquakes. These calculations require a knowledge of the probability of failure (fragility) of all safety-related components in the reactor system which would affect the outcome of the hypothesized accident scenarios.

Component failure is defined as either loss of pressure boundary integrity or loss of operability. Failure (fragility) is characterized by a cumulative distribution function which describes the

probability that failure has occurred given a value of loading. In the context of the SSMRP, loading may be local spectral acceleration, local zero period acceleration, or internal force resultant such as moment, depending on the component and failure mode under consideration. Contrary to previous work, fragility is related to the appropriate local response, rather than being related directly to free-field peak acceleration.

The initial determination of the necessary fragility functions has been completed. As a first step, all components identified in the reactor fault tree analyses have been grouped into 37 generic categories, and fragility functions have been determined for each category. For example, all motor-operated valves located on piping with diameters between 2.5 and 8 in. are placed into a single generic category, and similarly all motor control centers have been placed into another generic category. All piping, tees, elbows, butt welds, and reducer sections have been placed into one generic category, and scaling factors (depending on size, material, and temperature) are utilized to relate the individual piping components to a single master fragility curve. The 37 generic categories are shown in Table 2.

Fragility functions for the 37 generic categories have been developed based on a combination of design analysis reports, experimental data, and an extensive expert opinion survey. In this survey, questionnaires were sent to more than 250 recognized specialists in the nuclear industry (representing nuclear power system vendors, utilities, testing laboratories, nuclear component manufacturers, architect-engineers, and consultants) which resulted in 147 detailed responses covering (to varying degrees) virtually all the 37 generic categories. Responses to the questionnaires identified various failure modes as well as the failure percentiles as a function of loading.

A second source of information available was the generic design analyses performed by Westinghouse and various component manufacturers for components used in the Zion plant. In these analyses, the component was assumed to be excited by a base acceleration corresponding to a prescribed design spectrum. Then an analytical solution for the stresses or loads in the component was obtained. From these analytical solutions we obtained the acceleration at failure by extrapolating the stresses to our estimate of the ultimate stress capacity using a procedure due to Newmark.²¹ In

TABLE 2. Generic categories for components.

Mechanical		
● Reactor core assembly		● Large horizontal vessels
● Reactor pressure vessel		● Small-medium vessels and heat exchangers
● Pressurizer		● Large vertical centrifugal pumps with motor drive
● Steam generator		● Large vertical pumps
● Reactor coolant pump		● Motor-driven compressors
● Piping		● Large motor-operated valves
● Large vertical storage vessels with formed heads		● Large relief and check valves
● Large vertical storage tank—flat bottom		● Small valves
Electrical		
● Horizontal motors	● Auxiliary relay cabinets	● Cable trays
● Generators	● Local instruments	● Circuit breakers
● Battery racks	● Motor control centers	● Relays
● Switchgear	● Computers	● Ceramic insulators
● Dry transformers	● Light fixtures	● Communications equipment
● Control panels and racks	● Invertors	
Miscellaneous		
● Air handling units		● Duct work
● Instrument racks		● Hydraulic snubbers

this procedure, the acceleration at failure is determined from the relation

$$A_F = A_D F_S F_\mu \quad (1)$$

where A_D is design peak acceleration, F_S is the factor accounting for ultimate load capacity, and F_μ is the factor accounting for the inelastic energy absorption capability. Thus F_S scales up the design acceleration to the failure acceleration, assuming all loads (or stresses) are calculated by a linear elastic analysis, since the peak load (or stress) is proportional to peak acceleration.

Before failure occurs, however, a significant amount of inelastic deformation (and hence energy absorption) takes place. In this inelastic response range, the stress increases much more slowly than the peak acceleration. The actual acceleration at failure is much higher than that predicted by a linear analysis. This additional acceleration capacity is accounted for by the ductility factor F_μ . Complete details for these calculations are in Ref. 22.

The experimental data utilized in developing fragility curves were obtained from the results of component manufacturers' qualification tests, independent testing laboratory failure data and data obtained from the U.S. Corps of Engineers SAFEGUARDS Subsystem Hardness Assurance Program. These data were critically examined for

applicability and then statistically combined with the expert opinion survey data to produce the final fragility curves for the 37 generic component categories.

To illustrate the results of the fragility development, a number of typical log-normal fragility relations are presented in Table 3. For each category, the value of the median response at failure M and a value of β , the standard deviation of the natural logarithm, is given. The probability of the response A exceeding the strength is then given by

$$P_{\text{failure}} = \phi \left[\frac{\ln(A/M)}{\beta} \right]$$

where $\phi []$ is the standard normal cumulative distribution function available in any statistics text.

(For further information, contact M.P. Bohn, Ext. 3-0856, or L.E. Cover, Ext. 2-1306.)

Preliminary Results of Thermal Igniter Experiments in H₂-Air-Steam Environments

During the Three Mile Island nuclear accident of 1979, gaseous hydrogen was produced in the reactor vessel from the reaction of steam with the exposed zirconium fuel-rod cladding. This hydrogen eventually escaped through an open relief

TABLE 3. Selected fragility relations.

Category	Parameter	M_A	β_A	Lowest failure mode
PWR reactor vessel	SA at 4 Hz and 5%	3.72	0.18	Nozzle support failure
Pressurizer	SA at 8 Hz and 5%	2.00	0.39	Anchor bolt failure, support failure
Steam generator	SA at 8 Hz and 5%	4.00	0.27	Support leg buckling and failure
Coolant pump	SA at 4 Hz and 5%	2.64	0.34	Failure of connection to support leg
Diesel generator	A	0.65	0.33	Control system malfunction, oiling system failure
Large motor-operated valve	A	6.30	0.40	Electrical failure, actuator binding
6-in. pipe, carbon steel	M	2.44	0.18	Butt weld failure at 70°F
29-in. pipe, stainless steel	M	203.3	0.38	Straight pipe (2.5-in. thick) at 600°F
Motor control center	A	7.70	0.73	Circuit breaker trips
Cable trays	SA at 4 Hz and 5%	2.23	0.39	Weld and support failures
Control panels and racks	SA at 12 Hz and 5%	3.66	0.83	Instrument failure
Ceramic insulators	A	0.17	0.39	Breakage

SA = spectral acceleration of gravity (g); A = peak acceleration of gravity (g); and M = vector moment in in.-lb $\times 10^6$.

valve into the containment building. At some point the hydrogen-air-steam mixture was ignited, producing an estimated 28 psi pressure spike.

Postaccident calculations indicate that the containment building atmosphere included more hydrogen than previously expected during such an accident. This has caused the industry (and the Nuclear Regulatory Commission) to reevaluate the potential risk from hydrogen burns inside containment buildings, which are generally not designed to withstand an overpressure much larger than that experienced at TMI.

In an effort to reduce risks from such situations, the Tennessee Valley Authority (TVA) has proposed and installed an Interim Distributed Ignition System (IDIS) in the Sequoyah Nuclear Plant, which in late 1980 received its low power license. The IDIS consists of conventional diesel engine glow plugs distributed throughout the containment. These plugs are to be manually energized simultaneously, once hydrogen has been detected by the plant monitoring system during an accident. Their purpose is to initiate combustion as soon as the mixture will burn (presumably at low hydrogen concentrations), preventing the accumulation of a detonable atmosphere.

In July 1980 the NRC Office of Nuclear Reactor Regulation requested that Lawrence Livermore National Laboratory conduct a short-term test program to evaluate the functionality of these particular glow plugs in environments containing known concentrations of hydrogen, air, and steam. Initiated August 1, 1980, the experiment was designed, constructed, and tested by November 10, 1980. Details are reported in Ref. 23.

The objective of the LLNL program was specifically to assess the functionality, or capability to ignite the mixture, of the glow plugs proposed by the TVA. Mixtures to be studied ranged from 6 to 16% dry hydrogen, and 30 and 40% steam fractions, each with 8, 10, and 12% hydrogen.

Figure 14 is a schematic of the igniter test facility. The burns were contained in a 20-in.-diam by 60-in.-long pressure vessel with a working pressure of 200 psi. The vessel was modified by the addition of two 8-in.-i.d. ports and one 4-in. port, as well as threaded penetrations for plumbing and instrument connections. Saturated steam was supplied by a 300-lb/hr boiler at approximately 75 psi. Mixing of the contents was accomplished with an air-powered fan placed at one end of the chamber.

FIG. 14. H₂ igniter test schematic.

During this test series the glow plug was positioned 3 in. above the bottom of the vessel powered by a 14.4 VAC source (136 W). Figure 15 shows the test vessel and instrumentation.

All testing was conducted remotely at the LLNL high explosives test facility, Site 300.

Instrumentation

Primary data for the igniter tests included temperature and pressure measurements, and gas concentration analysis.

Test vessel temperature measurements were made with Chromel-Constantan (type E) thermocouples, indicating temperatures of the mixture inside the vessel, the vessel outer wall, and the ambient air at the facility. Pressure indications were provided by strain gage pressure transducers. Glow plug dynamic performance data included temperature, voltage, and current measurements.

Pressure measurements and most of the temperatures were recorded on high-speed frequency-modulated magnetic tape, then digitized and transferred to computer tape for filtering, reduction, and plotting on the LLNL CDC 7600 computers.

Gas analysis was accomplished by a 15-location sampling system and mass spectrometric analysis. The 75-cm³ sample bottles were evacuated before each test and mounted on the appropriate stations. One bottle was opened for 5 s before each glow plug activation, and another after a burn had been indicated. The mixture in the vessel was circulated before each sampling.

Test Results

Peak pressure as a function of hydrogen concentration is plotted in Fig. 16. Also shown is a dashed line representing the calculated maximum adiabatic pressure rises from dry hydrogen-air burns, calculated with the CECS code. Steam tests exhibit noticeably lower pressures for given hydrogen concentrations than dry tests. This is to be expected since steam acts as a diluent.

Completeness of combustion appears in Fig. 17. These data are consistent with results obtained in other test programs in that burn completion approaches 100% as the hydrogen concentration nears 9% for dry mixtures. The steam tests again evidenced less complete burns than dry concentrations.

Conclusions

This experimental program addressed thermal igniter functionality in a variety of hydrogen-air-steam environments to better understand the performance characteristics of an Interim Distributed Ignition System during a postulated Loss of Coolant Accident. The following conclusions can be drawn from the results:

- Thermal igniters are capable of combusting low concentrations of hydrogen in dry air, even below the 10% H₂. (The mixture should be combusted in this region to prevent potentially dangerous pressure pulses arising from higher concentration burns.) Although the low H₂ concentrations do not produce complete combustion, the range between 8 and 9% appears to be the transition to complete burn conditions. The transition to complete burn conditions with steam has not been clearly defined in these tests.

- Steam acts as a diluent in all cases, suppressing both the magnitude of the pressure rise and the completeness of burn.

- The glow plug performance did not appear to degrade throughout the test series.

- Circulation of the mixture enhances combustion, most apparently at lower H₂ concentrations.

The author expresses appreciation for support by the following individuals throughout the course of the program: Barry Bowman, Bill Comfort, and Dick Martin for initial experimental design and subsequent technical assistance; Del Eckels, Bill Shay, and John Holm for mechanical and instrumentation design, fabrication, and operation; Rex Blocker for program coordination; Bob Kaster for Site 300 bunker operation; and Charley Tinkler, U.S. NRC technical monitor.

(For further information, contact W.E. Lowry, Ext. 2-0270.)

Load Combination Program to Aid Nuclear Power Plant Design

Nuclear power plant structures, systems, and components are required by law to be designed to withstand the appropriate combination of the effects due to normal operation, natural phenomena, and postulated accidents.

The postulated accident loads, and loads caused by natural phenomena, are random events.

FIG. 15. Pressure vessel with instrumentation.

FIG. 16. Pressure rise as a function of H_2 concentration.

Amplitude, duration, frequency, time of occurrence, and time-phase relationship are random and stochastic in nature. Without a systematic probability assessment, it is difficult to come up with a rationale for appropriately combining events.

Current nuclear power plant design criteria have therefore been based on judgment toward conservatism, because no comprehensive probabilistic study and unified philosophy exists on which to base better-founded decisions. Consequently, safety margins between various systems and from plant to plant vary widely. Trying to follow the inconsistent and fragmented load combination requirements is frustrating to the nuclear industry.

The Load Combination Program, a multimillion dollar, long-term research program undertaken by the Lawrence Livermore National Laboratory, is a major effort to resolve these difficult and important issues. The program is funded by the U.S. Nuclear Regulatory Commission (NRC).

Current planning is that the program will continue through 1985. The long-term overall objectives are as follows:

- Define each individual load by these means:

- (a) Develop a methodology to estimate the reliability of typical piping systems, both inside and outside the containment structure, and provide the NRC with a sound technical basis for defining criteria for postulating pipe breaks.

FIG. 17. Burn completeness as a function of H_2 concentration.

- (b) Assist the NRC in defining individual dynamic load magnitudes and event occurrence rates.

- (c) Develop a methodology to estimate the dependency between events, for example, the probability of a loss-of-coolant accident (LOCA) or water hammer induced by earthquakes.

- Develop a methodology to establish load combination criteria for nuclear power plant design. This methodology should be capable of addressing basic issues with regard to which loads need to be combined, how they are to be combined, and what service level is applicable under the Boiler and Pressure Vessel Code of the American Society of Mechanical Engineers (ASME).

The first phase of the Load Combination Program started March 1979 and was completed at the end of the summer of 1980. The following objectives were addressed relating to two major issues:

- Estimate the probability of a large LOCA induced by earthquakes for a selected pressurized water reactor (PWR) plant and develop a probabilistic fracture mechanics model that can be used to estimate piping reliability in general.

- Develop a methodology for combining generic dynamic loads for nuclear power plant design.

The first objective requires the development of a deterministic fracture mechanics model for fatigue

crack growth. This model, incorporated with stochastic inputs of initial crack size distribution, material properties, stress histories, and leak detection probability, is used to calculate the probability of pipe leak subjected to the various loading conditions, including seismic. A schematic representation of the various steps in the analysis shows their interrelationships (Fig. 18). The "best estimate" model and approach were used in the computation. The probability results together with their uncertainties are used to determine whether low probability events such as a large LOCA and Safe Shutdown Earthquake (SSE) should be combined for the design of nuclear structures and components. Results indicate that the probability of a double-ended guillotine break, either with or without an earthquake, is very small (on the order of 10^{-12}). The probability of a leak was found to be several orders of magnitude greater than that of a complete pipe rupture. The results of our study have been used by the NRC as a basis to allow 24 PWR nuclear power plants to continue operating.

The development of a methodology for combining generic dynamic loads involves the computation of component reliability to derive the appropriate load combination requirements for nuclear power plant design. By considering event probability, the nature of these events, structural properties, response characteristics, and other random phenomena, this methodology will achieve greater consistency in component design than can be achieved with current practice. With this methodology, the NRC can evaluate component reliability implied by current design. The methodology can also be used to compare the component reliability implied by the use of the square root of the sum of the square (SRSS) and absolute sum (ABS) problem.

Two piping designs were used for illustration. The first example deals with an Essential Service Water (ESW) line in a PWR plant subjected to seismic and hydraulic transient loads, in addition to self-weight, thermal expansion, and internal pressure. The second example deals with a Steam Relief Valve (SRV) line from a typical boiling water reactor (BWR) Mark II plant subjected to normal, seismic, weight, thermal expansion, thermal transient, SRV building response, SRV steam hammer, SRV discharge, SRV drag, condensation oscillation, and chugging loading conditions. The proper load combination equations were developed for the

two systems based on component reliability criteria. A comparison between SRSS and ABS response combinations was also undertaken. The appropriate service level associated with each load combination case was discussed.

(For further information, contact C.K. Chou, Ext. 2-0215.)

Spill Test Facility for Liquefied Gaseous Fuels

The Lawrence Livermore National Laboratory, under the direction of the Department of Energy's Environmental and Safety Engineering Division, is participating in the Liquefied Gaseous Fuels (LGF) Safety and Environmental Control Assessment Program. The DOE goal is to provide safety information to industry, regulatory agencies, and the public for the selection of sites for LGF terminals and storage facilities and for the design and operation of these facilities, as well as transport facilities such as ships, rail cars, and trucks.

The principal objective of the LGF Spill Test Facility at the Nevada Test Site is to experimentally verify predictive computer models. Verifying the accuracy of the computer models requires a spill test facility capable of handling experiments of sufficient size and operational variability to test the models over a significant range of phenomena. Once verified, the models can then be used to accurately predict accidental spill effects 50 to 300 times larger than the verifying experiments.

The new test facility will be able to spill 10 to 500 m³ of LNG initially, and LPG, LNH₃, and LH₂ later. The experiments planned for the new facility involve spilling, evaporation, dispersion, burning, and explosion of LGFs at various rates, volumes, atmospheric conditions, and experimental arrangements.

The spill facility design concept (Fig. 19) consists of four 150-psi LGF storage tanks connected to a 1600-ft-long, 24-in.-diam insulated underground spill pipe which leads to a 1000-ft-diam spill pond. The center of the pond will be 25-ft deep. The LGF will be forced out of the tanks and out the spill pipe by 150-psi nitrogen or helium gas stored in two 2500-psi, 67-m³ pressure vessels. To drive out the LGF remaining in the spill pipe after the storage tanks are emptied, a cryogenic pipeline pig will be forced through the spill pipe by injecting 150-psi nitrogen gas behind the pig.

FIG. 18. Schematic representation of the various steps in the analysis shows their interrelationships.

FIG. 19. Arrangement of test facility for a 500-m³ LGF spill.

To conduct spills on dry soil, the shallow periphery of the spill pond will be drained and a 100-ft-long extension will be installed on the end of the spill pipe, extending it to the peripheral area. Various nozzles and splash plates will be installed on the end of the pipe to vary spill velocity and direction on or below the water. An array of experimental measurement sensors will be placed upwind and downwind from the spill point. The facility will be controlled and monitored by a control trailer located approximately 5 mi south of the tankage area.

(For further information, contact W. C. O'Neal, Ext. 2-8369.)

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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 Nonnuclear Ordnance Program, Organic Materials Division, and H (Physics) Division. We perform studies and develop hardware 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, hydrodynamics 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 R. A. Corallo, Ext. 2-8301.)

Livermore Flame Experiment Simulates LNG Spill and Ignition

As energy costs and demand continue to rise, the United States is faced with prospects of increasing imports of liquefied natural gas (LNG). In the event of an accident involving an LNG tanker, large quantities of spilled liquid would vaporize and thus form a large potentially explosive cloud. How this cloud would react and burn when ignited by a suitable ignition source is the subject of a multiyear, multimillion dollar program the Laboratory is conducting for the Department of Energy. The Laboratory is involved because of its computational capability to develop very large computer models of physical and chemical processes, and its experience with reactions involving large releases of energy.

In addition to field tests, which involved spills of four or five cubic meters of LNG at China Lake, Calif., small-scale laboratory tests were conducted by igniting gaseous mixtures of propane and air to provide statistical modeling data. Our test fixture was a flame bed (Fig. 1) 90 by 30 by 15 cm, open at the top and at one end to simulate an unconfined

FIG. 1. A schematic representation of the flame bed experiment.

geometry. The bottom of the flame bed served as a full-length plenum separated from the bed proper by a layer of porous material. The side walls consisted of optical-quality glass panels separated by vertical aluminum bars which contained transducers and ion gaps.

Photographing the flame front was done with a rotating drum, high-speed framing camera using light from an expanded argon-ion laser and schlieren mirrors. In operation, a premixed gas-air mixture stored in a gas bottle was introduced into the plenum and allowed to diffuse through the porous bed into the flame bed. Being heavier than air, most of the gas mixture stayed in the flame bed as it filled, aided by a drop door at the opposite end which was released just as the shot was fired. The ignition source was a capacitor bank across automotive spark plugs mounted on the end plate. We also had large glow plugs available to simulate other types of ignition sources.

Turbulent eddies disturb the flame surface area, causing a greater rate of energy release. In an actual spill, turbulence could come from a number of sources, such as houses, trees, low hills, wind, etc. We were able to successfully model this effect by using obstacles of different heights placed on the porous bed.

(For further information, contact S. J. Perry, Ext. 2-9644.)

FIG. 2. The x-ray water generator.

New X-Ray Water Blumlein System Measures Plasma Density More Accurately

A new water Blumlein x-ray generator has been designed and fabricated for x-ray diffraction and radiography experiments. The Blumlein (capacitive energy storage elements that are capable of producing a flat-topped output pulse) is currently being used on the Shiva/Nova Plasma Shutter experiment to measure the areal density of a plasma. This new system will have increased operating voltage, improved reliability, and a simpler design compared to the conventional polyethylene Blumlein.

The water Blumlein, as shown in Fig. 2, has a negative dc voltage applied to one side of a $0.3\text{-}\mu\text{F}$ low-inductance capacitor isolated from ground by a spark gap switch. The other side of the capacitor is connected to the inner conductor of the water line. A remote x-ray tube is connected to the output end of the Blumlein, with the inner conductor connected to the anode of the x-ray tube and the outer conductor to the cathode. Deionized water separates the inner and outer conductors.

FIG. 3. Arrangement of x-ray tube.

A plasma source with a particle density of 10^{21} ions cm^{-3} is being developed to block target reflected light from reentering the laser amplifiers on the Shiva/Nova system. A capacitor bank produces a current that heats a metal foil or wire to burst, producing a plasma. Contained in a railgun geometry, the plasma is magnetically propelled across the laser beam path. Current diagnostics using a Faraday cup and glass witness plates measure

plasma velocity and density. Using the water Blumlein, a second, more accurate method of determining plasma density is obtained.

The x-ray tube is mounted 90° from the plasma axis and a film pack is positioned within the axis of the x rays (Fig. 3). A radiograph is taken of the plasma and compared against a step wedge of aluminum and copper foils positioned within the field of view. Figure 4 shows a uniform plasma

FIG. 4. A uniform plasma propelled 5 mm.

propelled 5 mm. Using the water Blumlein, new plasma chip designs have been tested producing the most efficient plasma to block all reflected light.

(For further information, contact W.B. Graham, Ext. 2-9649.)

Stress Rupture Test System Developed for Composite Pressure Vessels

Long-term performance of high pressure composite vessels (Kevlar-epoxy) is being evaluated by LLNL project teams. The extreme importance of this evaluation led to the establishment and a recent upgrade of the hydraulic stress rupture testing system in the Division's High Pressure Engineering facility, Building 343.

A major concern associated with high pressure composite pressure vessels is the time-dependent failure criteria when the vessels are subjected to various stress levels. The long-term stress rupture system was developed to permit accurately setting and controlling the different stress levels as a function of time. The intent with this system is to

achieve such control by using high pressure plumbing hardware with precision gauges and transducers. The test units are connected to the system where the temperature is maintained nearly constant within a few degrees of 80°F.

Aircraft hydraulic fluid (type 5606) is used in the system (see Fig. 5) in current testing of vessels for the National Aeronautics and Space Administration. A feature of the long-term stress-rupture system includes placing more than 100 test units on station at several pressures. Test pressures up to 50 000 psi are available for different composite pressure vessel design configurations. The system illustrated in Fig. 5 can be used in either manual or instrumentation mode. The manual operation indicates the time to failure (minutes, hours, days) for the vessels. This is accomplished by actually checking the units on a regular basis by using the gauge and hydraulic supply system. The instrumentation mode, however, allows the experimenter to use various types of instruments, such as a pressure transducer, and strain and circumferential gauges. The data acquisition system associated with this instrumentation mode enables the test results to be recorded on tape.

FIG. 5. Long-term stress-rupture-system installed in Building 343.

The units on test are enclosed in a steel vessel that contains all the fragmentation when the pressure vessel bursts. The containment vessel is designed to satisfy the safety requirements of the Mechanical Engineering Department.

In a typical experiment, 10 to 30 vessels may be stored at three pressure levels at the long-term stress rupture facility. The desire is to combine the test

results from the stress rupture experiment with the appropriate analysis. Then we can expect to predict satisfactory performance of the fiber-reinforced pressure vessels for their final application.

(For further information, contact J.D. Cervelli, Ext. 2-9598.)

WEAPONS ENGINEERING DIVISION

Weapons Engineering Division (WED) is responsible for engineering activities supporting nuclear weapons development, production, and maintenance of a major portion of the national stockpile. In providing these services, the Division keeps abreast of new developments in safety, weapon control, and guaranteed weapon life extension.

Our activities include new weapon development, environmental testing, weapons control and enhanced safety, initiating systems development, engineering technology, and special materials procurement. Production work involves communicating product definition and design intent to the DOE contractors responsible for component fabrication and assembly. In addition, active monitoring of the stockpile requires a large effort in disassembly surveillance of stockpile weapons to ensure that design requirements have indeed been met

and to monitor physical changes that may eventually limit the useful life of a weapon.

The Special Materials (SM) office purchases goods and services from integrated contractors, military commands, and other governmental agencies for all LLNL programs. This office is also responsible for coordinating Laboratory guidance on weapon development activities by the integrated contractors, purchasing special isotopes used in a variety of programs, and providing the DOE with a forecast and management plan on nuclear material usage.

Because of classification restrictions, none of the numerous significant and important activities of the Weapons Engineering Division for the period covered by this issue of the Technical Review are being reported.

(For further information, contact R.E. Clough, Ext. 2-8721.)

ENERGY SYSTEMS ENGINEERING DIVISION

Our division provides mechanical engineering support to the Laser (Y) Program in two major categories: laser fusion (LF) and laser isotope separation (LIS). The LF effort is directed at understanding the basic physics problems associated with imploding small fusion targets with high power lasers, and at developing a fusion process to provide an unlimited source of power for use during the next century. In the LIS program, coherent laser light is used to selectively photoionize atoms of a given isotope in a material containing several isotopes. The ionized atoms can then be separated and enriched using extractor/collectors. Each major category has both military and civilian applications.

We highlight seven accomplishments in this issue that help to illustrate the work performed by the division.

- About 20% of our manpower is allocated to the Nova and an interim laser fusion research facility. We are helping to analyze, design, manufacture, and assemble components so that these facilities can be completed on schedule and within budget. Several unique aspects of these components are summarized.

- Fabrication of fusion targets is enhanced through the use of microradiography, which permits opaque targets to be completely inspected in only 45 minutes. Previously, it had required 1 to 2 days.

- We describe an ultra-violet holographic microinterferometer which permits picosecond probing of laser-induced plasmas. The microinterferometer provides time- and space-resolved photographs necessary for understanding characteristics of energy absorption processes.

- We have achieved nanosecond pulse-length laser action using metastable selenium atoms. This is a milestone in our efforts to develop a laser where energy can be added and stored in long-lived excited states, then extracted rapidly to achieve high output powers. Some physics and engineering questions must still be resolved before selenium lasers can become competitive for laser fusion applications.

- Rare-gas halide lasers are sensitive to acoustic pressure fluctuations that degrade the laser output power. We overcame this problem by adding an acoustic attenuator in the gas flow system. We have now achieved output powers that are a linear

function of the pulse repetition frequency, with a maximum value of 55 W.

- Our first large-scale LIS facility (Mars) for enriching uranium has been constructed and is currently undergoing activation; full-power operation is scheduled for the summer of 1981. The facility will be used to address large-scale physics and engineering issues.

- We have developed compact inexpensive heat shields that provide enough thermal insulation to yield optional plasma tube temperatures for a discharge-heated copper vapor laser. Of three heat shield designs analyzed, one constructed of fibrous alumina ceramic eliminates plasma tube failure due to dielectric breakdown.

(For further information, contact J.E. Keller, Jr., or J.R. Hauber, both at Ext. 2-7582.)

New Mechanical Technology Marks Design of the Nova Laser System

The Nova Laser Fusion Research Facility, which should be operational about 1985, will provide a new tool to study nuclear weapons physics and inertial confinement fusion.

The Department of Energy has approved Phase I construction of 10 laser beams and associated laboratory buildings. Funding for Phase II, which includes the remaining 10 beams and harmonic conversion crystal arrays, is under consideration by the DOE.

Between now and beginning operation of Nova, an interim machine will be built. It will have two beams identical to those of Nova and will probably use the Shiva target chamber. Shiva and Argus will be shut down by mid-1981 and operation of the interim machine will commence in late 1982.

This program is consistent with the goals of building a series of increasingly powerful and energetic laser systems of advanced concept. Nova will be the sixth major system at LLNL (see Table 1). All of the machines through Shiva have neodymium-glass systems at a wavelength of approximately 1.06 μm . Nova also will have the capability of operating at shorter wavelengths of 0.53 and 0.35 μm .

TABLE 1. Chronology of neodymium-glass laser development at LLNL.

Name	Power (TW)	Energy	Pulse length	First operational date	Cost (in millions of dollars)	Accomplishments
Cyclops	1.0	100 J	100 ps	1973-74	—	Laser chain development
Janus	0.4	40 J	100 ps	1974-75	—	First LLNL demonstration of thermonuclear neutrons
Argus	5	2 kJ	500 ps	1976	4	Shorter wave length target coupling
Shiva	28	10 kJ	350 ps	1977	30	100 times D-T liquid density
Novette	20	20 kJ	1 ns	1982	18	—
Nova Phase I	100	100 kJ	1 ns	1985	145	—
Nova Phase II	200	200 kJ	1 ns	Late 1980s	195 ^a	—

^aThe estimated cost will be \$238 million with shorter wavelength capability.

Development of this series of laser machines has required new engineering approaches that depart from classical lines. This has created a mechanical technology unique to laser fusion experimental systems. We are applying much of this technology to Nova in the advanced amplifier design, clean facilities, stable optical supports, and the design of a system dedicated to efficient maintenance so that our goal of maximum performance will be realized.

The LLNL laser technology also is being transferred to the British for their Helen laser at the Atomic Weapons Research Establishment (AWRE) to the Japanese for their 12-arm version of Shiva, named Gekko; and to the French for their proposed Nova-like two-beam system called Phébus. Some of the Laboratory's new technology is described in this summary.

This design work is being done by the following members of the mechanical systems group of the Nova project: J. R. Braucht, G. S. Bradley, J. B. Canfield, M. G. Demos, F. A. Frick, B. M. Gim, C. A. Hurley, G. C. Lee, A. Martos, C. B. McFann, Jr., R. C. McKee, H. J. Rien, R. L. Sites, I. F. Stowers, M. D. Virgino, and D. L. Watts. These are supported by a group of Kaiser Engineers personnel headed by Howard Julian.

Disk Amplifiers

The full Nova machine will require 280 disk amplifiers. One hundred of these will be salvaged from Shiva. The rest are new "box amplifier" designs with apertures of 20.8, 31.5, and 46 cm that

incorporate all the latest innovations of amplifier technology.

Box amplifiers are similar to the earlier disk amplifiers in several ways: the basic elements of disks, lamps, reflectors, and their close-packed relationship with each other, have not changed. However, the box design allows us to build large disk-containing amplifiers more economically and simpler than previous amplifiers. Figure 1 shows a cutaway view of a 46-cm box amplifier. Lamps in two opposite planes pump the disk faces. Light passes through the disk before striking other flashlamps.

The pump cavity is a rectangular box with six reflecting sides. Glass is placed between the lamps and disks (Fig. 1) to protect the disks from contamination and to control cooling gas flow. The inner box offers maximum reflectivity of the pump light.

The pump cavity is electrically isolated from the external box. This isolation guards the spaceframe from the high voltage (22 kV) that would be caused by flashlamp failure.

Easy assembly of fewer parts is compatible with cleanliness and safe handling of the expensive disks. Vertical positioning of disks has two advantages: they can be kept cleaner (a horizontal surface collects more contaminants than a vertical one) and will not deflect from their own weight.

The disk holders and reflectors are fabricated by electroforming, a cost-effective process which eliminates 50% of the machining normally required for these shapes. Flashlamps, backed by crenulated

FIG. 1. A 46-cm clear aperture disk amplifier. Neodymium-glass split disks and transverse flashlamps are unique features of this box amplifier.

reflectors are mounted to the side covers. For successful final assembly, strict attention must be paid to tools, procedures, fasteners, and fits, so that no contaminants are generated. Here dedicated design to simplicity pays off for easier assembly.

Spaceframe

System stability and accessibility are directly related to the spaceframe, which rigidly supports and is a key element in maintaining the alignment of the total system. Thermal and vibrational stability are the primary requirements of the spaceframe, which consists of four major elements. There are east and west laser frames; a switchyard frame, and a target frame. The length of the machine is approx-

imately 500 ft from east to west and approximately 120 ft north to south. Thermal motions of the frame are kept within tolerable limits by the strictly specified building environment.

Vibrational effects were modeled by simulating the motion of the frames using SAP4, a structural analysis code. For each frame structure, we performed a modal analysis to establish frequencies and mode shapes. The response of the structure was evaluated by performing a dynamic analysis using actual measured forcing-function data.

The undeformed laser frame and two higher-order modal shapes are shown in Fig. 2. Deformations of the frame were obtained using the measured forcing-function data. Deformations were within

FIG. 2. Computer-generated graphics for stability studies of the Nova laser frame.

acceptable limits with a maximum translation of $3.445\text{ }\mu\text{m}$ and a maximum rotation of $0.972\text{ }\mu\text{rad}$.

Spatial Filters

Spatial filters, located between amplifier stages, control beam propagation by filtering, relaying, and expanding the beam. There are seven in each laser chain.

They will be fixed to the spaceframe and the lenses will be brought on the beam axis with lens adjusters that have the capability of moving each lens in the x , y , and z directions under full vacuum.

Vacuum in the four largest spatial filters will be maintained with 1000 liter s cryogenic pumps. The remaining units will be pumped with vacuum pumping systems.

System

The sensitive nature of huge optical systems requires minimizing particulate contamination. Particles on optical surfaces result in surface damage

when exposed to flashlamp or laser light. Secondly, the units, the handling equipment, and the system must be designed so that everything can be reliably and easily maintained.

Because large components such as the turning mirrors (Fig. 3) need this special attention, the entire machine is in a class 10 000 clean room. In addition, we have an assembly clean room of class 100, which is used for assembling components. This room will be refurbished for handling new hardware.

For further information, contact C. Harles, Ext. 2-0681

Microradiographic System Developed to Measure Laser Target Balls

As part of the fabrication of laser fusion targets, we measure the physical parameters of the target balls before they are irradiated by the laser.

FIG. 3. Turning mirror blanks for Nova are made of borosilicate glass by Schott Optical Company.

In the past, one of our most common targets was a hollow glass microsphere that contained the deuterium-tritium fuel. These microspheres range in diameter from 70 to 200 μm (0.003 to 0.008 in.) and have wall thicknesses varying from 0.5 to 25 μm (0.00020 to 0.001 in.). Because these microspheres are transparent, microinterferometers have been used extensively to measure their wall thickness and uniformity. However, recent directly driven laser targets include microspheres coated with opaque layers of plastic polymers (CH_4 or CF_4). It is not feasible to use microinterferometers to measure the thickness and uniformity of these coatings, so we have developed a microradiographic system.

The microradiographic system consists of two separate parts: the monoenergetic x-ray system that generates the x rays to produce the microradiographs, and the Automatic X-ray Image Analysis System (AXIAS)¹ for analyzing the microradiographs once they have been produced.

A monoenergetic x-ray line is desirable because for a given thickness of coating material there is a single energy that maximizes the information recorded on the film plate. If the energy is too high, there is almost no absorption and the microsphere is transparent to the x rays. If the energy is too low, the microsphere is opaque to the x rays and there is no penetration. We can easily calculate the optimum energy for the microsphere we wish to examine, and then choose the correct characteristic x-ray line.

The monoenergetic x-ray source consists of an annular LaB_6 cathode, and a conically shaped water-cooled anode (Fig. 4). The anodes have standard Cajon fittings so that anodes of different materials may be used. By selecting an appropriate accelerating voltage, we can excite a characteristic x-ray line in the anode material. We also obtain background bremsstrahlung radiation, but by carefully choosing the accelerating voltage we can maximize the ratio of the characteristic x-ray line to the bremsstrahlung background.

The spectra produced by our x-ray source can be further improved by absorption filtering of the unwanted portion. Figure 5(a) shows the spectrum from a silver anode. The spectrum includes the silver L line at 2.98 keV; the bremsstrahlung background with superimposed characteristic lines from the stainless steel walls of the vacuum system; and the silver K_α and K_β lines at 22.1 and 24.9 keV, respectively. By filtering this spectrum through

FIG. 4. Monoenergetic x-ray system.

FIG. 5. Spectrums (a) from a silver anode at 40 keV and (b) from a silver anode at 40 keV using a 0.020-in.-thick aluminum filter.

0.020 in. of aluminum, we can obtain the spectrum shown in Fig. 5(b). Here we have only the silver K_{α} and K_{β} lines.

Once the radiograph of the microsphere has been made, the information about coating thickness and uniformity that has been stored as variations in film exposure (optical density) is analyzed by the AXIAS system. The image is magnified with a white-light microscope, digitized, and stored in an image processor. We can then take optical density scans across the image and record the density variations as a function of position. Then we use a least-squares fitting routine to do a four-parameter fit to the data from the density scan.

To verify the accuracy of the system, we used it to analyze several glass microspheres that had been

characterized optically with an interferometer. The radiograph, density trace, and fitted data are shown in Figs. 6 and 7(a) and 7(b). The experimentally tested uncertainties in the measurement of microsphere parameters can be stated as a percentage of the values measured. There is, however, an absolute minimum. Table 2 shows a list of the typical uncertainties of the radiographic measurements and the minimum uncertainty of this technique.

With our new analytical capabilities we can now select a microsphere, radiograph it, and analyze the data to the accuracies listed in Table 2, all within 45 min. This is a major improvement over the 1 to 2 days necessary using our old technique and makes the microradiography system a useful

FIG. 6. Radiograph of a 150- μ m-diam glass ball.

FIG. 7. (a) The optical density scan across the radiograph and (b) the least-squares fit to the data from the density scan.

TABLE 2. Accuracy of the least-squares fitting routine.

Parameter	Typical uncertainty (%)	Minimum uncertainty (μm)
Diameter	1	1.0
Wall	1	0.5
Nonconcentricity	3 (of wall)	0.05

and production-oriented tool for examining opaque targets.

For further information, contact J. J. Weir, Ext. 2-5891, N R Rile, Ext. 2-5947, or D. E. Perkins, Ext. 2-9085.

Designing an Ultraviolet Holographic Microinterferometer for Plasma Probing

One of the techniques to help understand the absorption of energy within laser-produced plasmas utilizes an ultraviolet holographic microinterferometer. The microinterferometer provides time- and space-resolved picosecond probing of plasmas with electron densities of 10^{20} to 10^{21} e/cm^3 and density contour velocities of 10^6 to 10^7 cm/s . Spatial resolution of $1\text{ }\mu\text{m}$ or better with pulse duration of 3 to 30 ps can be obtained.

The design has some main functions. First a portion of the main laser pulse is split just after the pulse selector and its subsequent amplification. Second, the $1.06\text{-}\mu\text{m}$ 30-ps pulse is filtered and then

shaped using a spatial filter and apodized aperture. Third, the laser pulse is frequency quadrupled using successive KD*P and ADP frequency doubling crystals. Fourth, to record data an interferometer is used that is simple, fits entrance and exit ports of the target chamber, has a path-matching capability of 0.5 mm with access to alignment controls, and has $f/2.5$ optics corrected for spherical aberration. Targets used in the experiments consisted of 40-to-80- μm -diam SiO_2 hollow microspheres or balls. The smaller sized balls were used to minimize the effects of probe beam refraction during passage through the strong axial gradient density field. In the dense plasma region, long wavelengths are refracted out at steep angles, missing the collection optics and therefore not exposing the photographic plate. The timing of events was accomplished within 10 ps with the aid of an optical streak camera.

The plasma experiments were performed at 1.06- μm wavelength with one beam of the Janus

laser facility. Incident energy on target was varied between 0.5 and 5 J in 30-ps pulses.

The illumination of the target area must be sufficient to expose a holographic film plate of about 3 cm^2 area. This requires a total UV energy on the film plate of 6 μJ . Because of losses in the optical system, approximately 15 μJ are required at the output of the frequency quadrupled crystal.

The interferometer is basically a Mach-Zehnder-type except that it is holographic and it utilizes a microscope objective to image the target with micron spatial resolution. Since it is holographic, focusing during plasma experiments is not critical. This is particularly important because the wavelength is ultraviolet. Focusing to micron accuracy is necessary for accurate interpretation of the fringes obtained.

The 2660 $\text{\AA}$ beam is split by a 37° prism (Fig. 8) into two beams, a reference beam and an object beam, of which the object beam passes through the

FIG. 8. UV holographic microinterferometer and target chamber.

target area. These two beams travel equal paths and then recombine to form very fine interference fringes. Upon reconstruction, the two images interfere to produce an interferometric fringe pattern characteristic of the plasma.

Bright reconstruction holograms require accurate matching of reference and object path lengths to less than the coherence length of the laser pulse. For a 15-ps UV pulse the maximum separation of these path lengths is about 0.5 mm. It is therefore necessary to move one of the reflectors with a resolution of better than 0.5 mm without changing angular alignment.

A 10×0.2 numerical aperture microscope objective is used to image the 40- μm diam microballoons behind the holographic plate. The reference beam is expanded by a 5-cm lens to illuminate three times the area of the object beam at the film plane. The shape of the interference fringes is determined by the difference in optical path traveled by the light ray refracted through the dense plasma area and the same ray through vacuum. Examples of fringe patterns surrounding laser-irradiated targets are shown in Figs. 9 through 11.

The UV probing technique described here provided the most detailed information ever obtained on the plasma surrounding laser/fusion targets.² The first photograph (Fig. 9) shows a 76- μm -diam microballoon used as a reference shot to obtain proper focusing. The second is a double exposure hologram with the target in place and then

removed to reveal a set of fringes without being irradiated by the 1.06- μm beam. These interferograms reveal the uniformity of the wall thickness. The third photograph is a shot taken 300 ps after the peak of the pulse. Here the fringes reveal the electron distribution.

The shape and density of the plasma protrusion in front of the target can be measured by the resulting fringes. It is necessary at this point to be able to resolve fringes with a resolution of 1 μm to measure density near critical, 10^{21} e/cm³. Figures 10 and 11 depict this plasma protrusion very well. The target in Fig. 10 is a 41- μm -diam glass microballoon, while Fig. 11 is a 70- μm -diam paralyene disk, both irradiated with the same laser intensity. The path length in Fig. 9 is seen to be about 20 μm for fringe 5, allowing us to estimate the average electron density in that region as about 2×10^{21} e/cm³. A method of accurately transforming the fringe full data to detailed point by point electron densities is referred to as Abel inversion. The technique which works for axisymmetric geometries such as ours, has been used by Sweeney³ to analyze the results presented here.

Conclusion

Optical probing through the target atmosphere is an important diagnostic tool for characterizing the plasma area. This is where the energy is absorbed and transported to the core region. This instrument then becomes a useful diagnostic tool to

FIG. 9. UV interferometer photographs: (a) single shot showing target only, (b) double shot showing uniformity of wall thickness, and (c) irradiated target showing fringes.

FIG. 10 Irradiated target illustrating fringes with original target diameter.

FIG. 11. Irradiated disk, paralyne target, illustrating fringes.

determine the density distribution⁴ in the critical region from 10^{20} to 10^{21} e/cm^3 . Typical target experiments involve 40- μm glass microballoons imploded with a 1.064- μm 30-ps pulse at intensities on target of 10^{14} to 10^{16} W/cm^2 . Resolution was measured to 1 μm by measuring the separation of the fringes in the reference hologram and comparing this measurement to the known ball diameter. Velocities as high as 5×10^6 cm/s were observed in triple exposures. Density scale lengths as short as 1 μm were observed. From these observations, it is imperative that, in the design of a holographic microinterferometer,⁵ the beam be in the UV and of short duration (15 ps) to probe the dense plasma area near critical density.

(For further information, contact E. L. Pierce, Ext. 2-5880.)

Lasers Based on Selenium $^{1}\text{S}_0$ Metastable Atoms

The laser program at the Lawrence Livermore National Laboratory continues to seek short-pulse lasers which would ultimately be capable of achieving the extremely high output powers required to produce thermonuclear fusion of laser-irradiated targets. One approach is to store energy in long-lived excited states (e.g., metastable states) of a suitable atom and then to extract that energy in a pulse of a few nanoseconds. The selenium laser was recently studied in this regard.⁶

The basic experimental system was derived from earlier published work⁷⁻¹⁰ and consisted of a high-current-density electron beam source which injected its beam into a cell filled with high-purity xenon gas. The 172-nm wavelength vacuum ultraviolet (VUV) light produced by xenon excimers (Xe_2^+) was then used to photolyze carbonyl selenide (OCSe) in an adjacent cell. Selenium ^{1}S metastable atoms were formed by photolysis, providing the basis for laser oscillation.

Figure 12 shows the energy levels and transition of interest for selenium. The wavelength of the $^{1}\text{S}_0 - ^{1}\text{D}_2$ "auroral line" is 776.8 nm (infrared) and the wavelength of the $^{1}\text{S}_0 - ^3\text{P}_1$ "transauroral line" is 488.7 nm (blue-green). These names are derived from the names commonly applied to the corresponding transitions of oxygen frequently observed in emission from the upper atmosphere. The oxygen $^{1}\text{S}_0 - ^{1}\text{D}_2$ line is the green emission seen in the aurora borealis.

FIG. 12. Energy levels of selenium. The laser transitions of interest are at 488.7 and 776.8 nm. Photoionization of $\text{Se} (^1\text{S})$ can occur by absorption of the 172-nm pump radiation.

Apparatus

The nominal voltage of the electron beam was 1 MeV for 50 ns. A two-bladed carbon cathode was used to form an electron beam over an area of 50 by 7.5 cm. The cathode was directly opposite a ribbed structure which supported a 0.127-mm-thick titanium foil through which an electron beam current of approximately 50 kA passed into the rare-gas VUV cell. The anode was simply the high pressure rare-gas cell (Fig. 13).

Identical photolytic cells were placed at each end of the rare-gas VUV cell. One cell was used for laser work and kinetic studies (Fig. 14) and the other was used to house VUV pump diagnostics. The photolytic cells were made of stainless steel and were separated from the rare-gas VUV cell by magnesium fluoride (MgF_2) windows. For fluorescence studies, the excited volume was viewed through MgF_2 reentrant windows; for laser experiments, the mirror mount assemblies shown in Fig. 14 were utilized.

During kinetics studies, a photomultiplier was used to view fluorescence through appropriate bandpass filters. To obtain fluorescence spectra of

FIG. 13. Cutaway view of the electron-beam source and high pressure rare-gas cell used to produce rare-gas-excimer radiation.

the photolytically excited gas, an optical multichannel analyzer attached to a spectrometer was used. Laser time-dependence was observed using photodiodes. E-beam-produced x-ray signals were reduced by using lead shielding around diagnostics, and electrical interference was reduced to acceptable levels by using rf shielded cables from the diagnostics to a screen room where the electronic readouts were housed.

Results

Laser action was successfully achieved on both the 489-nm $\text{Se}(^1\text{S}_0 - ^3\text{P}_1)$ "transauroral line" and the 777-nm $\text{Se}(^1\text{S}_0 - ^1\text{D}_2)$ "auroral line." The OCSe

molecules in the laser volume were totally dissociated by the VUV radiation.

The large fluences of VUV radiation used to photolyze the OCSe molecules were found to produce significant concentrations of free electrons by photoionization of the product ^1S atoms. This process is indicated schematically in Fig. 12. The free electrons can rapidly deactivate the ^1S atoms and thus greatly limit laser performance. Small concentrations of sulfur hexafluoride (SF_6) were found to counteract this problem by attaching the photoelectrons so that their quenching was not significant. For optimum selenium laser performance, 1 Torr of OCSe mixed with 5 Torr of SF_6

FIG. 14. Cutaway view of the photolytic cell used for experiments with selenium lasers. The laser mirrors are mounted within the cell.

and 50 Torr of CO was photolyzed. The CO provided deactivation of the lower state as well as electron cooling. The latter enhanced electron attachment by SF_6 .

Collision broadening and collision-induced emission were both observed to affect $\text{Se}^{\text{I}}(\text{S})$ gain. In conjunction with this effort, XeSe and KrSe collision-induced lasers were demonstrated for the first time simply by adding several atmospheres of xenon or krypton, respectively, to the photolytic mixture.

Laser performance on both the $\text{Se}^{\text{I}}(\text{S}_0 - ^3\text{P}_1)$ and $\text{Se}^{\text{I}}(\text{S}_0 - ^1\text{D}_2)$ lines was optimized by varying the photolytic mixture, the VUV pump fluence, and the output coupling of the laser mirrors. Laser output was approximately constant for VUV fluences between 125 and 200 mJ/cm^2 . The OCSe was completely dissociated over the laser aperture for these fluences. Above 200 mJ/cm^2 the laser output slowly declined, presumably because of $\text{Se}^{\text{I}}(\text{S})$ losses associated with photoionization. For optimum conditions the output energy from a volume of 6.5 cm^3 was 25 mJ for the blue line and 16 mJ for the infrared line. Although the total energies were small,

the volumetric output, about 4 J/liter, was respectable.

Conclusion

The practicality and potential size of a $\text{Se}^{\text{I}}(\text{S})$ laser amplifier is limited by the $\text{Se}^{\text{I}}(\text{S})$ storage time and the depth of OCSe that can be totally dissociated. Collisional deactivation of $\text{Se}^{\text{I}}(\text{S})$ limits the pump duration to a few hundred nanoseconds at 1 Torr of OCSe. $\text{Se}^{\text{I}}(\text{S})$ losses associated with photoionization limit Xe_2^* fluences to 250 mJ/cm^2 . This fluence is sufficient to totally dissociate 1 Torr of OCSe with two-sided pumping over a maximum aperture of 14 cm. With that aperture an output laser energy of several kilojoules is reasonable for a $\text{Se}^{\text{I}}(\text{S})$ amplifier long enough to produce outputs approaching the window damage limit of 10 J/ cm^2 .

However, several engineering problems must be solved if high energy selenium lasers are to become practical for fusion applications:

- The pump must be closely coupled to the lasing medium to produce good light coupling efficiency (preferably with a large aspect ratio of illuminated height-to-photolysis depth).
- Superfluorescence in the pump must be controlled.
- Broad-area e-beams must have magnetically isolated modules to prevent beam pinching.
- If a window separates the laser gas mixture from the fluorescer, optical damage problems from VUV photons, scattered electrons, and x rays as well as mechanical fracture due to shock waves must be solved.
- If a windowless geometry is used, laser-gas and fluorescer-gas mixing problems must be solved.

Should an efficient VUV laser be developed which could replace the e-beam pumped fluorescer, several of the difficulties just noted would not exist. However, window and mirror damage problems would still need solutions.

The selenium laser system could become competitive for fusion applications if answers are forthcoming on the several issues previously mentioned and, more importantly, if other more efficient chemical or kinetic means are found for production of the $\text{Se}^{\text{I}}(\text{S})$ excited state.

(For further information, contact B. R. Schlichter, Ext. 240185, or H. F. Powell, Ext. 24149.)

Acoustic Attenuation in the Closed-Cycle Test-Bed Laser

The Closed-Cycle Test-Bed (CCTB) (Fig. 15) is a repetitively pulsed, transverse-flow, electric-discharge laser built to determine if Rare Gas Halide (RGH) lasers can be scaled-up to an average power system, in this case typically tens of watts. One concern is the effect of the pressure waves generated by the pulsed electric discharge on the laser performance. The discharge deposits electric energy into a small volume of gas, the discharge region, heating and partially ionizing it. Because of the very short duration of the electric pulse (~ 100 ns), the gas does not have enough time to achieve thermodynamic equilibrium. The result is an abrupt pressure and temperature change in this region, which can be approximated by a constant volume heating process given by

$$\frac{P_2}{P_0} = \frac{T_2}{T_0} = 1 + \frac{E}{C_v T_0},$$

where P = pressure,

T = temperature,

E = energy input per unit mass,

C_v = specific heat at constant volume,

subscript 0 = at system conditions,

2 = after heat addition.

This ratio is typically in the range of 1 to 1.5. After the electrical energy has been deposited in the gas, the discharge region expands, reducing the pressure of the system. The region of hot gas is then transported downstream by the gas flow. This expansion of the discharge region is the source of the acoustic pressure waves which are transmitted and

FIG. 15. Closed-cycle test-bed (CCTB) laser flow loop.

reflected inside the flow loop. From one-dimensional shock-tube theory, the peak amplitude of the initial pressure wave (P_1) can be approximated by the following implicit expression:

$$\frac{P_2}{P_0} = \frac{P_1}{P_0} \left[1 - \frac{\frac{T_0}{T_2} \left(\frac{P_1}{P_0} - 1 \right)}{\sqrt{2\gamma} \sqrt{2\gamma + (\gamma + 1) \left(\frac{P_1}{P_0} - 1 \right)}} \right]^{\frac{-2\gamma}{\gamma - 1}}$$

where P = pressure.

T = temperature.

γ = ratio of specific heats.

subscript 0 = at system conditions.

1 = for the pressure wave.

2 = after heat addition.

Under operating conditions (2 atm, 25°C, and an energy input of 45 J/g), these equations predict peak amplitude of the pressure wave, corrected for duct area expansion, of 12 kPa. This value corresponds to a measured value of 15 kPa or a peak sound pressure level of 180 dB. The wave will decay from this level, because of the viscosity and thermal conductive properties of the gas and duct geometry effects, to a steady-state value of a few kPa or about 160 dB.

At these acoustic levels, the pressure fluctuations degrade the laser output power by apparently reducing the uniformity of the gas breakdown voltage in the electric-discharge region. We overcome this problem by adding an acoustic attenuator or muffler into the flow system. The attenuator converts the highly organized structure of the pressure waves into uncoordinated random motions of thermal vibration. This can be accomplished by replacing the hard duct walls with a porous sheet which allows the pressure waves to be transmitted through the small passages in the material where viscous effects convert them into thermal energy. The muffler must also have a low through-flow pressure loss, from a system efficiency viewpoint.

The CCTB has a single acoustic muffler section that is close-coupled to the downstream side of the laser head. It is a rectangular cross-section duct that houses two resistive sidewall absorbers with backing volume. The two sidewall plates are 520-mm wide and 247 mm in the flow direction. The duct height is

30 mm, with a backing depth of 14 mm. This corresponds to a muffler length of 8 h (where h is the duct height) and a backing depth of 0.5 h. The only source of through-flow pressure loss for this duct section is skin friction. The acoustic resistive material used is a nickel-felt metal. This material was selected because of its chemical stability with the halogen gases used. The acoustic flow resistance (impedance) of the felt metal is 68 cgs rays. This value was selected to be a close match to the characteristic impedance of the system gas, which is 53 cgs rays. The reduction of a pressure wave transmitted through the muffler has been measured to be 20 dB, but further work must be done to reduce the steady-state sound-pressure level in the electrode region which remains high. The addition of the muffler has resulted in a retuning of the acoustic characteristics of the flow loop. Some changes in the laser performance, which can be partially attributed to the muffler, are the reduction of the extreme sensitivity in the output power at specific values of the pulse repetition frequency (PRF), and a removal of the average power roll-off observed for PRFs in the 300-to-500-Hz range. The output power is now a linear function of PRF, with a maximum value of 55 W.

(For further information, contact J. M. Davin, Ext. 2-0868, or J. W. Dickie, Ext. 2-6262.)

Design of the Mars Experiment to Prove Economical Enrichment of Uranium

The Mars experiment is part of the ongoing Atomic Vapor Laser Isotope Separation (AVLIS) program in which we are attempting to economically enrich uranium for nuclear power plant application.

The process consists of vaporizing uranium in a vacuum furnace using electron-beam (e-beam) guns as the heating source. The vapor flows through an extractor process section where the ^{235}U atoms are ionized in a tuned laser beam. The product and tails are collected individually in a flow cycle compatible with a plant's operation.

The physics process has been demonstrated and the Mars project is our first attempt at a large-scale system that will serve as a major subsystem integration test facility.

Figure 16 shows the Mars experiment module. The vessel configuration consists of three 5.5-ft-diam stainless steel cylindrical chambers of single-wall construction. The vessel arrangement is serial. Two smaller satellite vessels straddle the center source vessel. These satellite chambers contain the optics for folding the laser beam through the center chamber. The center or source chamber contains a copper hearth and e-beam gun assemblies, extractor, background collector, and provisions for uranium feeding and material output. The three-tank concept gives us the ability to isolate the optical components during vaporizer startup and also minimizes the risk of optics contamination during maintenance and routine cleanup.

The approximately 14-ft-long center source vessel opens along a horizontal separating plane. This concept permits operational access to both the source and optics vessels for maintenance and system alignment and provides stable structural support for the three subsystems. Center vessel opening is done by vertically raising the upper tank

half which is supported by four ball-drive screws and is guided by a rectangular support frame. Lid activation is accomplished from a local control panel in the experiment bay. The light-tunnel connections are unlatched, and the bellows flange assemblies are compressed to provide the necessary clearance before lifting the main lid. Sealing across the horizontal flange is accomplished with two 1.4-in.-diam Viton-A O-ring seals. The upper half of the source vessel contains two 30-in. openings that provide the laser interface with the satellite vessels. Two 30-in.-diam sliding-gate valves isolate the three vessels.

Internal cooling for the source vessel is accomplished by contoured heat-exchanger panels (Fig. 17). The overlapping panel installation provides the necessary x-ray shielding across the horizontal flange-separating joint and facilitates cleanup. These panels line the upper half of the vessel, including end domes, and extend 18 in. into the lower section where they interface with horizontal panels that terminate at the source. The panel

FIG. 16. Three-chamber Mars vacuum vessel.

FIG. 17. Satellite-vessel optics isolation.

concept is a cost-effective means of providing a cold-wall vessel without constructing a double-wall vessel.

The lower half of the main vessel is firmly mounted to the slab floor by two support cradles, which are connected internally to the vessel by two large box-type keel beams. This structure serves as a rigid support pallet for the source subsystem. Square tubes or box beams were selected to provide cooling if necessary. The main vessel contains ports for utility services, diagnostics, material feed, and contingencies. Conflat seals are used on the port flanges.

Electron-beam steering is controlled by externally mounted Helmholtz coils, which are split at the vessel's horizontal separation flange. Multilam connectors are used to allow for coil separation

The upper vessel lid is aligned during closing by tapered guide pins located in the lower flange. These guides provide the proper alignment for connector engagement. Helmholtz coils are located 1 m apart over the source.

Each satellite optics vessel is supported by four canted legs belted directly to the slab floor. The end doors are mounted on davits to provide access. A single pedestal of 18-in. diam, bolted to the inertial base located below the optics tank, extends into the vessel through a bottom port. The pedestal is attached to the vessel by a metal bellows section. This provides vessel sealing and decouples the pedestal-mounted optics from tank deflections and vibrational disturbances. The concept is shown in Fig. 17.

Vacuum Pumping System

The multiple-vessel vacuum system operates in the 10^{-5} Torr range. The system provides roughing- and high-vacuum pumpdown times of approximately 2 h. System sizing was based on scaling existing facilities with a provision for additional loading from graphite components. A single 35-in. oil-diffusion pump (DP) provides 15 000-liter/s pumping speed at the inlet to the main chamber. The satellite optics vessels are pumped through bypass connections from the main vessel. Because of cost, a single DP system was selected rather than pumps for each satellite. However, the baseline system is adaptable to separate DPs since the backing system is sized for this contingency. The system can rough or hard pump any of the three vessels serially or simultaneously. For satellite-chamber maintenance, the main chamber can be held at vacuum while a satellite is brought to atmospheric pressure, then returned to operational status. The system contains optically tight cryogenic baffling in the main- and fore-pumping lines to protect the optics from oil backstreaming.

Heat-Exchanger Pumping System

The subsystems in the Mars main chamber requiring cooling water are as follows: copper hearth, e-beam guns, source cooling shroud, vessel liner, keel-beam structure, and diagnostic probes. The Mars crucible subsystem, which was designed and developed by Oak Ridge National Laboratory, requires high velocity cooling—up to 50 ft/s. Consistent with our reliability and safety criteria, the system provides closed-loop cooling for all the chamber internal systems. The pumping system consists of a centrifugal (two-stage) 150-hp motor-driven pump with nominal capacity of 500 gal/min at a deliverable head of 250 psi. The tubular heat exchanger is capable of rejecting 1.5-MW thermal to our base low-conductivity water (LCW) system. The primary cooling loop contains a filtration bypass pump and provision for chemical water treatment. This system is a palletized pumping station interfacing with facility LCW and city water. The city water can provide emergency cooling of the crucible in case of a power failure or loss of pump pressure.

Ventilation System

Consistent with Laboratory safety standards and the design criteria in effect on existing AVLIS

facilities, the Mars system contains a negative air system in the vessel to prevent inhalation of uranium particles and to provide direct containment. The ventilation system will maintain an air-face velocity of 150 ft/min across the open areas of the vessel system.

System Integration

The Mars experiment is currently on schedule. Low power e-beam gun tests are completed and uranium handling and vaporization began in mid-February 1981. The Mars project team successfully completed Phase I facility activation and now the mechanical engineering team is involved in design/engineering of support diagnostics, feeder subsystems, and the logistics of a material handling system. Full power operation is anticipated by July 1981.

For further information, contact Y. Oster, Ext. 2-6113.

Discharge-Heated Copper Vapor Laser Heat Shields

The heat shield region of a longitudinal discharge, discharge-heated copper vapor laser (DHCVL), which is shown in Fig. 18, is critical to overall laser performance. The DHCVL utilizes the waste heat generated in an inert gas (and copper vapor) pulsed electrical discharge to heat a cylindrical plasma tube to a high operating temperature (1400 to 1600°C). At the same time this electrical discharge must provide the copper atom population inversion required for lasing action.

The high operational temperature is required to vaporize copper in a sufficient amount to provide the optimum copper atom number density for efficient laser operation. The heat shield must provide only enough thermal insulation to yield the plasma tube temperature for optimal laser operation within the constraints of input power (electric discharge waste heat), copper atom number density, output power, and axial temperature profile. Because of those requirements, detailed thermal analysis capability is necessary to better understand operating lasers, as well as to investigate large geometries for laser scaling studies.

In the development of DHCVLs, three different heat shield designs have been utilized: metallic, hybrid nonmetallic, and nonmetallic.

FIG. 18. Copper vapor laser.

Because of the high temperatures involved, the metallic thermal radiation shield was the first one used [Fig 19(a)]. It was fabricated into a cylinder of spiral-wound molybdenum foil (<4.8 -cm-diam over a 3.2-cm-diam plasma tube) separated by a large-mesh tungsten screen and operated in a vacuum. The vacuum essentially eliminated radial gaseous conduction and convection losses, the screen minimized radial metallic contact (conduction) losses, and the molybdenum foil layers minimized thermal radiation losses. The metallic heat shield wraps must be installed so there is no contact with the alumina plasma tube to avoid dielectric breakdown of the alumina because of the difference between the capacitively coupled heat shield voltage and the plasma voltage. However, because of their radial compactness, metallic heat shields are the primary types utilized for the majority of small-bore DHCVLs in operation.

The second type of DHCVL heat shield developed was the hybrid nonmetallic design shown in Fig. 19(b). This heat shield configuration was developed to provide a package that was as radially compact as the metallic heat shields, but that was constructed of more readily available and less costly components. This was accomplished by utilizing a combination of fibrous alumina and zirconia cylinders surrounded by several spiral wrapped layers of

molybdenum and nickel foils separated by alumina cement and operated in a vacuum. The fibrous ceramics were not of sufficient thermal efficiency for this small diameter to eliminate the use of metal foil wraps altogether. However, a significant reduction in the molybdenum foil usage and a total elimination of the tungsten screen was realized. Also, because the metal foil layers were displaced a much greater distance from the plasma tube in this design, problems associated with dielectric breakdown of the alumina plasma tube were also reduced.

The third type of heat shield developed for DHCVL operation is one constructed entirely of a fibrous alumina ceramic [see Fig. 19(c)]. Because the nonmetallic heat shield material has an effective thermal conductivity greater than that of a metallic or hybrid nonmetallic heat shield, this construction is utilized primarily with large-bore copper lasers where there is more waste heat available and the cylindrical geometry is more favorable. However, nonmetallic heat shields have been utilized for small-bore copper lasers with increased diameter vacuum jackets (heat shield diameter <6.3 cm). Because of the electrical insulating properties of the fibrous alumina, use of the nonmetallic heat shields essentially eliminates plasma tube failure due to dielectric breakdown.

FIG. 19. (a) Cylindrical-metallic, (b) hybrid-nonmetallic, and (c) nonmetallic heat-shield arrangements for small-bore DHCVL operation.

The capability to predict the thermal characteristics of these heat shield designs is very important to DHCVL operation. Computer calculational methods have been developed to predict both axial and radial temperature profiles of cylindrical copper lasers operating with the heat shield designs previously described. This capability has provided a great amount of insight into the thermal characteristics of both operating lasers and proposed large-bore lasers for scaling limit studies.

Figure 20 presents calculated performance maps for metallic heat shields (constructed of eight

metal foil wraps) necessary for a 2.5-cm-diam copper laser. The information is presented in a manner such that the known (or projected) waste heat characteristics of the laser can be combined with the emissive properties of the metal foil layers to determine the maximum (center) plasma tube temperature that will be achieved. By determining similar graphs for heat shields with different numbers of total metal wraps, the number of wraps necessary to achieve a particular maximum plasma tube temperature can be determined. Once a particular heat shield assembly and operating conditions have been chosen, the axial and radial temperature profiles can be calculated.

Figure 21 presents a comparison between the measured and calculated axial temperature profile of a large-bore (7.3-cm-diam) DHCVL operating with a nonmetallic heat shield. The operating conditions and calculation parameters are listed in the figure for reference. The thermal conductivity utilized is a quadratic curve fit to information given by the manufacturer of the heat shield material. The heat flux (DHCVL waste heat) used in the calculation was adjusted for best agreement with the measured maximum temperature. As can be seen, this resulted in an 11% difference between the calculated and measured heat flux values. This difference can be attributed to errors in the thermal conductivity utilized.

The primary interest in the comparison of Fig. 21 is in the excellent agreement between the experimental and predicted axial temperature profiles. The axial temperature profile is of great importance to DHCVL operation since it determines the active laser length, and thus the overall laser light output. Because of the excellent agreement between the measured and predicted results, it can be concluded that accurate predictions of the thermal characteristics of copper lasers can be accomplished. Because of this, information concerning particular laser geometry thermal design as well as information pertaining to general laser scaling can be obtained. This capability has resulted in a substantial reduction in the experimental time required to bring a conceptual DHCVL into full operational capability.

For further information contact F. W. Alger Ext. 2-6194 or W. J. Bennett Ext. 2-6040

FIG. 20. Plasma tube (2.5-cm diam) center temperature as a function of the applied heat flux or the metal foil emissivity for a metallic heat shield with eight foil wraps.

FIG. 21. Experimental and computed plasma tube (7.3-cm diam) axial temperature profile comparison.

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ENGINEERING SCIENCES DIVISION

The Engineering Sciences Division (ESD) provides complete technical services for materials characterization, engineering measurements, non-destructive evaluation, and mechanical systems design and evaluation. The Division has more than 20 separate laboratories and facilities that are organized into sections responsible for specific technology areas.

The Materials Test and Evaluation Section provides mechanical testing, such as ASTM standard tests and special tests tailored to individual customer requirements. Development is a major effort in the fields of acoustic emission, fracture mechanics, high-rate response, and composite materials evaluation.

The Engineering Measurements Section is engaged in work ranging from calibration of a single transducer to fielding complete measurements systems. Service for the calibration and installation of transducers and accelerometers is available.

The Nondestructive Evaluation Section provides quality-assurance services and engineering inspection for LLNL programs. Nondestructive 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.

The Engineering Design Section designs and fabricates hardware to support the Chemistry and Materials Science Department, the Earth Sciences Division, and ESD itself. A major effort is support of the tritium facility operation.

The Life Sciences Group provides mechanical engineering support for Biomed and Environmental Research, Hazards Control, and Toxic Waste Management programs. Specific examples such as the cell sorter in Biomed, personnel dosimetry equipment in Hazards Control, and storage and/or burial containers for toxic wastes, give some idea of the varied requirements in these areas.

The LLNL Plutonium Facility is managed by the Chemistry and Materials Science Department with operational support provided in part by ESD. The Plutonium Engineering Section in ESD provides engineering design, fabrication, and testing services for the Facility and its users.

The Transportation and Mechanical Energy Storage Section provides research, technical assess-

ment, and planning support for DOE programs in transportation systems and energy storage. Examples of mechanical storage technology under consideration include flywheels, elastically deformed polymers, and compressed fluids. A major transportation project is the study of roadway-powered electric vehicle systems.

(For further information, contact R. W. Werne, Ext. 2-8360.)

Developing a Facility for Fatigue and Fracture Testing of Stainless Steel Weldments and Base Metal at Liquid Helium Temperatures

We have designed a mechanical test facility to evaluate fatigue and fracture toughness properties of stainless steel weldments and base metal at liquid helium temperatures. This is a joint effort between the Engineering Sciences and Magnetic Fusion Engineering Divisions to study the cryogenic behavior of materials selected for the structural cases of the MFTF-B magnet system.

Fabrication of these structures requires welding thick sections. For this reason, along with the higher stresses produced from the increased operating intensity of magnetic fields at 4 K, we are concerned about the structural integrity of both welds and base metal.

In planning the test facility, we had several design considerations. With the higher cost of liquid helium, we placed high priority on minimizing its usage. We considered the natural and forced convection of liquid helium and the heat-conduction properties of the test fixture when selecting materials and designing the cryogenic load train. Hollow compression columns and a modified pivot plate were specially designed to reduce the mass of stainless steel exposed to liquid helium. We were also concerned with the facility cost and ease of operation, i.e., access to specimen grips and disposal of liquid helium and liquid nitrogen. We therefore decided on a mechanical testing system test machine with a crosshead-mounted actuator which allows the entire cryogenic load train to be lowered into the liquid helium Dewar (Fig. 1). Special rubber and synthane rings provide thermal

FIG. 1. The Materials Test and Evaluation Section's new Cryogenic Test Facility is capable of testing fracture toughness at loads up to 55 kip in a liquid helium environment. Staff members around the system are (left to right) E. N. Dolder (MFE), D. S. Hiromoto (MTE), D. B. Duncan (Engineering Design), M. C. Johns (MTE), R. R. Vandervoort (MTE), and R. D. Streit (MTE).

insulation of the load train from the actuator and load frame.

We expect to begin a fracture mechanics test program in the near future. Our immediate testing will include J-integral evaluation; however, we also plan fatigue crack growth studies and tensile testing.

(For further information, contact M. C. Juhas, Ext. 3-1254, D. B. Duncan, Ext. 2-8463, or R. D. Streil, Ext. 2-7045.)

Flash Radiography with a 2.3-MeV Febetron

Over the past year the flash radiography capability of the Nondestructive Evaluation Section (NDE) has been enhanced with the refurbishment of a Field Emission (now Hewlett-Packard) Febetron machine. The unit is on loan from the Laboratory's Y Program where it had been used as

an electron beam source. Funding, which is through a reimbursable project on propellant studies from the Chemistry Department, brought the unit out of storage and made possible its conversion for x-ray production. Byron Kitt of the NDE section has worked extensively on refurbishing and operating the unit.

Figure 2 shows the unit and its control console. The peak x-ray energy is 2.3 MeV with a pulse width of 30 ns. This short duration flash can stop the motion of very fast dynamic events. Figure 3 is a flash radiograph taken with this unit at Site 300. A high velocity steel projectile strikes a large (150-mm-diam by 100-mm-thick) disk of propellant. The shock and deformation of the propellant are recorded by the radiograph. The radiographic information is used in the evaluation of propellant detonation characteristics.

(For further information, contact R. H. Bossi, Ext. 2-0431.)

FIG. 2. Febetron 705 flash x-ray machine and control console. The machine uses a Marx generator capacitor bank charged in parallel at 30 kV and discharged in series for a maximum 2.3 MeV. The x rays are generated by the field emission principle in a special x-ray tube located at the end of the capacitor bank.

Holographic Evaluation of Composite Structural Bulkheads

Thermal stress holographic interferometry is being used for the nondestructive evaluation of composite structural bulkheads made of composite materials. Delamination, fiber breakage, and overall quality of the composite material is of interest. The holographic examination of the composite structural bulkhead is performed before hydrostatic testing, after a predetermined hydrostatic pressure test, and after the part has failed.

The thermal stress test can be performed in either a real-time or double-exposure holographic technique. In the double-exposure method the first exposure of the composite structural bulkhead is made at ambient temperature. The composite structural bulkhead is then heated with a heat lamp and monitored with a thermocouple to a maximum temperature of 150°F. The composite structural bulkhead is then allowed to cool to 90°F and the second exposure is made (see Fig. 4).

This work is being performed as part of a nondestructive evaluation program to determine the best method to measure the quality of the composite domes after the hydrostatic proof test. Future holographic testing of composite structural bulkheads will include continued thermal stressing and the development of a hydrostatic testing procedure.

(For further information, contact W. W. Wilcox, Ext. 2-7269 or D. M. Boyd, Ext. 2-7971.)

The Use of Pulsed Light Sources to Characterize Materials

When a pulse of light energy of sufficient amplitude impinges upon a material, an elastic stress wave will be generated in that material. Several mechanisms account for this effect. A pulse of low energy (~ 0.10 J) will produce a thermally generated stress wave, whereas a high energy pulse (~ 15 J) will generate a stress pulse as a result of material vaporization and blowoff. In either case the resulting stress wave can be used to determine the material's sonic velocity, its elastic constants, and to detect flaws in the material.

The purpose of this research project has been to explore a variety of available pulsed light sources for suitable stress wave generation, to examine various methods of detecting these stress waves, and

FIG. 3. Flash x-ray radiograph of a propellant object. The 100-by-150-mm-diam propellant object is struck from the left by a steel projectile 150 mm in diameter. The projectile is fired at the object from a 155-mm gun.

to apply the concept to materials characterization in a nondestructive manner.

During the final quarter of this fiscal year, primary emphasis was placed on investigating techniques of water-immersion testing using a Q-pulsed Nd-glass laser. Using fiber optic bundles, the laser energy could be easily directed to an immersed specimen for stress wave generation. Several secondary parameters were also explored, which included comparison of the responses of a variety of transducers as well as investigating the potential of using displacement interferometry in conjunction with water immersion testing.

Several different experimental arrangements have been used in the water immersion technique. These are shown in Figs. 5(a) through 5(d). Figure 5(a) shows the specimen placed in a glass-walled water tank. The energy from a Q-switched laser is directed through the glass wall of the container, through the water interface to the specimen. Previous tests have shown that the angle of incidence of the incoming laser pulse to the specimen is not particularly critical for angles as great as 60°. This makes geometrically flexible and therefore extremely convenient detection of the resultant laser-generated stress waves with an immersed ultrasonic transducer.

The arrangement shown in Fig. 5(b), where the sensing transducer is located behind the specimen,

FIG. 4. Three holograms of a composite structural bulkhead: (a) shows the part after thermal stressing but before hydrostatic testing. The "fish tail" fringe pattern near the upper left of the part indicates a possible delamination site. (b) shows spurious fringe patterns near the edge in the upper left and lower right portions of the composite structural bulkhead, indicating abnormal surface movement. (c) shows that the composite structural bulkhead failed close to areas depicted by the spurious fringe patterns in (b).

gave results similar to those obtained using the arrangement of Fig. 5(a). In both cases the stress wave transit time could be accurately determined and the specimen's sonic velocity calculated.

Figure 5(c) shows the immersion testing scheme using a fiber optic bundle to direct the laser energy to the sample. The advantage of this technique is the ability to direct energy to any part of the specimen. The sample may also be oriented in a manner which is most convenient for recording the resulting stress wave with either an ultrasonic transducer or with displacement interferometry.

In Fig. 5(d) the combined use of fiber optics and displacement interferometry is depicted. This combination can be extremely useful for testing

components with complicated geometries or in hazardous environments.

An evaluation of the response of a variety of transducers was made in order to determine which transducer or transducers were most suitable for detecting the laser-generated stress waves and for flaw detection. Transducers evaluated included 0.5, 1, 5, 10, and 20 MHz PZT (lead-zirconate-titanate) and lithium sulfate transducers, one-dimensional strain lithium niobate transducers, and quartz transducers.

It has previously been shown that the width of the stress pulse generated by a 30-ns laser pulse is on the order of 100 to 200 ns in most metals. Because of this the higher-frequency transducers proved to

FIG. 5. Four different arrangements were made for the test specimen: In (a) the laser energy is directed through a glass tank to the front surface and in (b) to the rear surface of the sample. An ultrasonic transducer records the sonic velocity in both cases. In (c) and (d) a fiber optic bundle directs the laser energy to the immersed sample. An ultrasonic transducer records the sonic velocity in (c), but a Michelson displacement interferometer is used in (d).

be more accurate in recording the stress wave arrival times and were also more suitable for flaw detection. A desirable feature of the piezoceramic transducers is their high sensitivity when compared to that of the quartz transducers. The quartz transducer is valuable for making actual strain measurements, but is not suitable for flaw detection purposes.

The displacement interferometer is the most versatile "transducer" for use in sonic velocity measurements. It can be used for flaw detection as well, but is only valid as a qualitative measuring tool in this case. Because of its sensitivity ($\sim \lambda/10$), its potential for locating flaws of submillimeter size is very promising.

Much still needs to be done to assess the potential of using laser-generated stress waves in non-destructive evaluation methods. Flaw detection using this method should be a separate study.

Materials characterization using pulsed light sources has been shown to be a viable technique when assessing sonic velocities, elastic constants, and for flaw detection. Various detection techniques, which include piezoceramic and quartz transducers as well as displacement interferometry have been shown to be useful and compatible for detecting laser-generated stress waves. Successful examination of materials to determine their properties and characteristics and to locate flaws in them has been carried out in a noncontact and non-destructive manner. The potential remains high for further development as a very useful NDE tool.

(For further information, contact W. W. Wilcox, Ext. 2-7269.)

Flywheel Energy Storage Systems for Use with Photovoltaic Power Sources

The Flywheel Energy Storage System (FESS) is intended to enhance the value and utility of small solar power generating plants. The timely development of economical energy storage concepts is crucial in many solar power applications. The variable nature of solar energy severely limits its applications if some practical storage systems are not made available. Batteries, pumped-hydro, compressed air, thermal and mechanical energy storage all offer the potential for suitable systems applica-

tions. Economic factors may favor one system in a particular application and yet another in a different application, depending upon performance and cost characteristics. However, at present accurate cost and performance characteristics do not exist for emerging technologies. New designs with generous margins of safety have not yet been demonstrated for mechanical energy storage systems. A FESS concept which could lead toward a practical demonstration is presented. The basic design goals are summarized in Table I.

Solar photovoltaic (PV) power systems presently being developed invariably use electric storage batteries when on-site energy storage is required. Moreover, studies of future PV power systems assume continued use of batteries for on-site storage, albeit with more advanced, efficient, and inexpensive battery designs. This predominance is due at least in part to the generally held conviction that no other on-site storage system can compete economically with batteries for PV usage. However, studies performed show that flywheel energy storage can be technically and economically competitive with either present-day or advanced storage batteries if the flywheel storage system is properly configured. This conclusion was reached after comparing battery and flywheel storage in a

TABLE I. Principal design goals for the system.

Parameter	Design goals
Electrical interface (FESS)	
Line-to-line voltage (V)	Below 220 (3-phase)
Frequency (Hz)	Below 400
Power in (kW)	4.0
Power out	
Intermittent (5 min), kW	6
Steady-state (kW)	
Available energy (kW·h)	7.5
Energy stored (kW·h)	10
Rotor density (W·h/lb)	20
Energy losses	
Motor (%)	5.0
Generator (%)	5.0
All other losses (%/hr)	0.5
Life expectancy (yr)	20
Cyclic life minimum full charge/discharge (cycles)	10 000

systems context, whereby their influence on other subsystems (such as inverters) was determined.

The essence of this approach is to utilize the flywheel subsystem for more than the energy storage function. A PV power system usually requires an inverter to convert the low-voltage dc output from the solar arrays to a (usually) higher voltage ac waveform. This operation can be performed by the flywheel unit with the use of a dc drive motor and a permanent magnet alternator. Also, it is usually necessary to provide a good impedance match between the PV array and the load in order to maximize the electric power extracted from the array. This function, commonly referred to as maximum power tracking, can also be provided by the flywheel. Figure 6 shows the system block diagram comparison of a battery system and inverter, a conventional flywheel with dc input and output followed by a dc-to-ac inverter, and a combined flywheel storage and power conditioning system. The simplicity of the last block diagram reflects the real cost savings possible with this implementation. These simplifications hinge on the use of an efficient, low-drag motor-generator and low-drag high-speed bearings, such as magnetic bearings.

System Concept

The Flywheel Energy Storage System has a dc motor, an energy storage flywheel, and a 60-Hz ac generator. It is supported on magnetic bearings in a vacuum housing, which would do double duty as safety containment for the flywheel rotor. The motor-generator is, in fact, the same device with separate input and output electronics. The detailed system is shown in Fig. 7.

All solar electric power goes through the dc motor to spin up the rotor. The motor is a dc brushless, ironless armature-type design controlled as a maximum power tracker for the solar array. This is important because the varying electrical output of a solar array is generally mismatched to the characteristics of the storage system and load, causing inefficient operation. The flywheel rotor is an advanced design. The electrical output is accomplished by use of a permanent magnet brushless generator and a silicon-controlled rectifier (SCR) cycle-converter. The generator is sized to accept the large surge demands of many candidate loads.

The entire rotating unit is supported on a dc magnetic bearing which is powered by windings on the motor allowing fail-safe, spin-down operation.

FIG. 6. Solar PV system comparison.

The resulting rotating unit would have no brushes or physical contact with the rotor, allowing very long life and high reliability. Also, the higher speeds (perhaps 20,000 rpm) possible with such an assembly allow smaller rotor size and enhance the quality of available ac power. Mechanical touchdown bearings are included for cold start-stop conditions with no rotating seals being required.

The vacuum chamber ensures a relatively long energy storage time before aerodynamic losses become a problem. The unit can be placed underground to provide additional safety containment. The system is run over a 2:1 speed range with the output voltage held at 60 Hz and generated independently or synchronized to an external line. This corresponds to a 75% depth of discharge for the flywheel energy storage function compared to 20% for proposed advanced batteries. Another feature is that the flywheel unit will be able to "cold start" from solar PV input power. This is done by deriving dc control power from the dc input until the wheel is up to speed, and using the maximum

FIG. 7. Detailed FESS representation.

power tracking feature of the input power circuit to avoid pulling the input voltage down too low.

The terminals of the motor-generator serve as a summing junction for motoring and generating currents, both kept synchronous by the electronics. This allows arbitrary combinations of charging and discharging power levels within the design range of the unit.

An attractive practical application for this device is to utilize it with a PV-powered single-family residence operating in either a stand-alone mode or coupled to a utility, with utility power drawn only during off-peak hours and only when the energy reserve in the flywheel is low. It can be scaled up to larger sizes associated with multiple

dwelling units or commercial PV applications. The residential system concept is illustrated in Fig. 8.

(For further information, contact D. M. King, Ext. 2-0312)

Concentrator Optical Geometry Diagnostics of Large Installed Arrays Using a Distant Observer

A simple method for determining the geometrical accuracy of parabolic trough modules in large, installed arrays is described. It is based on the principle that a distant observer, when looking

FIG. 8. Residential flywheel energy storage system.

into the aperture of a concentrator will see an enlarged image of the receiver pipe reflected in the mirror. The position and size of the image depends on the distance and angular position of the observer relative to the collector and can easily be predicted for ideal collector geometry. The differences between these predictions and what is actually observed can be used to identify and quantify specific geometrical errors, including receiver pipe misplacement and mirror slope errors.

As the parabolic trough is rotated from tracking to stowed position, a series of observations are recorded by a 35-mm motion picture camera from a fixed position at least 10 focal lengths away. The distance from observer to collector is measured with a precision hand-held ranging device. Many modules can be tested from a single location since displacement along the collector axis is unimportant. The observer may need to be elevated to see modules in the second and subsequent rows. A power pole, rooftop, or other existing structure may be used as observer locations, but a hoist or scaffold may be necessary.

Measurements are made in the laboratory with a projection system and a position-digitizing screen with electronic stylus. The data are reduced and plotted by the computer. (Alternatively, a less precise plot could be made by hand from a few points.) By comparison with plots for collectors with known errors, the geometrical accuracy (or lack of it) can be determined and specific errors identified and quantified.

Techniques exist for more precise optical testing of parabolic troughs in the laboratory. The laser-ray trace is the most noted method. Portable variations on the ray trace hardware for laboratory use have been developed by Sandia National Laboratories, Albuquerque, New Mexico, to allow testing of collectors installed at its outdoor testing facility. These tests are designed primarily as a check on the quality of the tooling, handling, and other manufacturing processes that produced the collector initially. Although they are well-suited for that purpose, they are not appropriate for field testing of large installed arrays. The hardware is not very portable, test setup time is long, and only one

module can be tested for each setup, implying considerable system downtime to test the whole array. Finally, the laser-ray trace method tests only the mirror shape; no indication is given of the positioning of the receiver pipe relative to the mirror.

An alternative method involves repeated thermal performance measurements at various off-optimum tracking angles. This method is considered less appropriate for field testing of installed collectors because it requires too much system downtime and system modifications, and it is too indirect to differentiate between specific geometrical errors.

Owners and operators of large arrays of concentrating collectors may wish to check out or tune-up their systems periodically. They may not care to take the manufacturer's word that the collector geometry is right. Installers may wish additional checks on their alignment procedures. In any of these cases, they need a test that gives accurate diagnostic information with minimum site modifications, minimum system downtime, and site-dedicated hardware. We believe the photographic distance observer method to be the best for these on-site testing purposes.

For further information, contact R.L. Wood, Ext. 2-1461.

Composite-Laminate Rotor Development

The LLNL has been involved since 1978 in the development of fiber-composite flywheels. Specifically, the objectives of the LLNL effort are to develop the technology for high-energy-density, fiber-composite flywheels based on the laminated-disk concept, and to demonstrate a prototype of this design for a practical flywheel application.

During 1980, four tapered-thickness, laminated disk flywheels were manufactured: two of Celion 6000 graphite/epoxy and two of S-2 glass/epoxy composites. They were 24-in. o.d., 1-in. thick (nominal) at the center, with a taper approximating the "Stodola" uniform stress contour.

Three flat disk flywheels were also produced. One was S-2 glass/epoxy, 15-in. o.d. by 0.42-in. thick. A second was also S-2 glass/epoxy, 11-in. o.d. by 0.8-in. thick. The third was Celion 6000 graphite/epoxy, 12-in. o.d. by 1.0-in. thick.

Aluminum hubs for these wheels were bonded to the disks at LLNL using a urethane elastomer bonding process developed at LLNL.

Figures 9, 10, and 11 show the tapered-thickness graphite/epoxy, S-2 glass/epoxy, and the constant thickness S-2 glass/epoxy disks, respectively.

FIG. 9. Tapered thickness graphite/epoxy disk.

FIG. 10. Tapered thickness S-2 glass/epoxy disk.

FIG. 11. Constant thickness S-2 glass/epoxy disk.

Four of these seven flywheels have been spin-tested. One of the graphite/epoxy tapered disks was tested at the Oak Ridge Flywheel Evaluation Laboratory. The other graphite/epoxy tapered disk, one S-2 glass/epoxy tapered disk, and the 15-in.-o.d. S-2 glass/epoxy flat disk were tested at the Applied Physics Laboratory, Johns Hopkins University.

The two graphite/epoxy tapered flywheels failed at an energy density of about 25 W·h/lb. For the S-2 glass/epoxy tapered disk, energy density at burst was 13 W·h/lb. Failure occurred by delamination between layers along the tapered contour.

It appears that failure of the tapered disk flywheel is probably precipitated by interlaminar shear stresses resulting from the contouring of the laminate. These stresses occur when the laminate is subject to in-plane tensile stress. (These stresses are absent for the flat disk, except at the edges.)

On the other hand, the flat S-2 glass/epoxy flywheel failed at 30.5 W·h/lb, notably higher than the 20 W·h/lb anticipated. This represents the highest energy density obtained for a laminated disk design. Although the flywheel disintegrated at failure, the failure mode was benign. There were some fibers in the debris that were 12 in. in length (Fig. 12). It was noted that the hub still had approximately two layers of S-2 glass bonded to the elastomer. The number one containment ring (out of four rings) was apparently unscratched, but there was evidence that it had rotated several revolutions after failure of the flywheel.

It is hypothesized that laminated disks will resist higher biaxial stresses than uniaxial stresses. Since the material samples were tested uniaxially, these values were used for predicting the performance of the flat disk S-2 glass/epoxy flywheel. The spin-test performance of the flat disk flywheel appears to bear out the biaxial strengthening effect.

The hub-to-wheel elastomeric attachment performed successfully in all tests thus far.

(For further information, contact S.V. Kulkarni, Ext. 2-7128.)

Study Conducted to Determine Feasibility of a Toroidal Traction-Drive System

Mechanical energy storage technology (MEST) is applicable to a variety of vehicles in the transportation sector. It has the potential for contributing towards significant energy conservation by (1) reusing energy normally expended in braking, and (2) by optimizing the prime mover energy rates for more efficient operation. Recently, flywheel energy storage technology has been used by the University of Wisconsin and the Marshall Oil Company. They demonstrated that by incorporating flywheel units with conventional, heat engine powered vehicles, significant fuel economy benefits may be achieved. However, for the heat engine flywheel (HE FW) system to be successful, an efficient, continuously variable transmission (CVT) system must be developed.

The objective of this study was to investigate different CVT-component systems and the associated transmission components necessary to assemble a CVT system capable of meeting the specifications determined necessary for obtaining significant fuel economy. It considers off-center, toroidal, traction drives. Preliminary design layouts of various systems were analyzed using computer simulation; a detailed analysis for each CVT design was performed by Traction Propulsion Incorporated (TPI), including efficiency estimates, contact stresses, life prediction, and film temperatures.

The toroidal-type drive unit has been designed and built by TPI for incorporation into a number of different applications. It has proven to be of sound design, quiet, capable of withstanding high speeds and shock loading, efficient, and relatively easy to

FIG. 12. Test debits of LLNL S-2 glass/epoxy flat disk.

manufacture. Lubrication within the traction-drive design is effected by a low pressure pump (20 psi, 2 gpm). Monsanto traction fluid, Santotrac 40, will be used for all internal lubrication. An oil-to-water heat exchanger will be used to cool the oil. The exchanger will not only transfer heat to the engine cooling water, but it will also transfer heat to the transmission oil during cold startup.

Control of the toroidal traction-drive unit will be accomplished by hydraulic means. A medium-pressure (~200 psi), low-flow pump will be employed. The transmission design requires no more than 0.25 gpm of control oil. All ratio controls will be automatic in response to signals from the accelerator pedal and from ratio-sensing transducers.

Four CVT systems were considered initially feasible for this application:

- Continuously variable drive (CVD) with a powershift.

- Two CVDs in series.
- Regenerative CVD.
- Multimoded CVD.

Each of the four configurations for the drive line system provides a workable alternative for use in the heat engine/flywheel-drive vehicle. The relative acceptability of the systems is largely a function of operating efficiency and acceptance of the system performance by vehicle operators.

Fixed-ratio, traction-drive speed reducers are included in each system to reduce the flywheel speeds to a level within the operating limits of the heat engine. For the dual-CVD system, a reduction ratio of about 3.75 to 1 is required, as the flywheel CVT will further reduce the speed as necessary. The other three systems require a ratio of 6 to 1, depending on the amount of additional reduction supplied in the power train. For high speed flywheels, a fixed-ratio speed reducer and clutch

should be placed between the flywheel and its CVT. The efficiency of the speed reducer, operated at full load and speed, is between 96 and 98%. Half of the losses are speed-dependent. The rest of the losses are torque-dependent; the efficiencies, which are calculated at the rated speed and half power, show twice the percentage loss as those calculated at full load.

The ratio range available from the CVT affects both the operating efficiency and the overall system performance. A highly efficient, but narrow-ratioed CVT may show a lower system efficiency than a less efficient CVT with a wider range. This is due to the operating characteristics of an internal combustion engine and the amount of clutch slip necessary to accelerate the vehicle up to a speed which can synchronize with the flywheel input. For this reason a wider ratio range than the 12 to 1 is recommended.

The multimoded CVD (Fig. 13) appears to be the best choice for the HE/FW vehicle. It has a wide

ratio range (60 to 1) with the best efficiencies of the systems studied.

(For further information, contact D.N. Frank, Ext. 2-1742.)

Ultrasonic Inspection of the MFTF Magnet Cover Welds

The first magnet pair for the Mirror Fusion Test Facility (MFTF) has been fabricated (see Fig. 14). The cover for the superconducting magnets is a 400-ton stainless steel weldment ranging in thickness from 76 mm (3 in.) to 127 mm (5 in.) Early calculations of maximum stress and strength of the material at liquid helium temperature indicated that the "worst case" critical flaw sizes would be on the order of 4.8 mm (3/16 in.).

FIG. 13. A schematic of a CVT utilizing a multimode CVD.

FIG. 14. John Ambrosino and Derrill Rikard of the Nondestructive Evaluation Section perform ultrasonic evaluation of the MTF Yie-Yang magnet case.

The inspection technique best suited for this weldment was ultrasonics. However, ultrasonic inspection of stainless steel welds has always been difficult due to the variability introduced by grain size and orientation in the weld material. A dual-transducer technique suggested and perfected by a transducer manufacturing firm, KB-Aerotech, was used. The inspection involved hand scanning by technicians Derrill Rikard and John Ambrosino of the Nondestructive Evaluation Section, Ken Sumikawa of the Engineering Measurement Section and Glen Nypiuk of the Materials Test and Evaluation Section, on more than 600 m of weld over a period of a year. The inspection was accomplished under extremely adverse conditions involving the weather, noise, scheduling to avoid working under welders, climbing around on scaffolding, and interpreting quite complex results.

Figure 15 shows the transducers coupled to a reference block and the ultrasonic data display instrument. The instrument performs three functions:

- It supplies the driving energy in short-duration pulses to the transmitting transducer to produce the ultrasonic waves.

- It amplifies the electrical signal produced by the receiving transducer.

- And it displays the electrical signals that are wideband pulses of approximately $2\ \mu\text{s}$, with a center frequency of 1.5 MHz.

The operator observes the location of the reflected pulses in time to interpret the depth of the flaw indication and the amplitude to determine its approximate size. Calibration reference blocks were made to determine the sensitivity and variability of the transducer response at various depths for both double-sided V-groove welds and one-sided V-groove closure welds. The closure welds were made over a backup bar. Variations in the fit produced a variety of reflections that interfered with the interpretation of data in those regions. The interpretation required a thorough knowledge of the range of fit that might exist and a visualization of what the results indicated in order to make a rather subjective evaluation of the data.

Ultrasonic reflections that were determined to be flaws and were greater in amplitude than that received from the end of a 4.8-mm-diam (3/16-in.) flat-bottom hole were recorded. Flaw indications

FIG. 15. Ultrasonic instrument, transducers, and stainless steel calibration reference piece.

that appeared to be greater than 6 mm (1/4 in.) were repaired.

The repairs were made by arc-air-gouging the weld material out and rewelding. Many of the flaws were found during the gouging process. They could be seen in the cooling metal just behind the arc. Slag inclusions were easily seen, but lack of fusion was more difficult. Some lack of fusion or cracklike indications were found by using dye penetrants after each pass of the arc-air-gouging.

As mentioned, the major difficulty was interpretation of results in the root of the closure weld where backup bars were required. Further develop-

ment to decrease the ultrasonic beam size could improve the lateral resolution by a factor of 4.

The results of the ultrasonic inspection of the MFTF magnet case weld were encouraging. Further development is planned that will considerably improve the interpretation of data. Improvements in the inspection time required are imperative since the next phase, the MFTF-B, includes another mirror magnet pair like that just completed, plus 14 solenoid coils and 4 C-shaped shaping coils.

(For further information, contact B. J. McKinley, Ext. 2-7974.)

MAGNETIC FUSION ENGINEERING DIVISION

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

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

Although the goals differ greatly, the three areas share a common technology base. Support is needed from virtually all mechanical engineering disciplines, as well as from engineers specializing in normal and superconducting magnetics, cryogenic systems, vacuum systems, high-voltage components, and nucleonics.

Our role in MFE confinement experiments is to provide the systems engineering, design, and fabrication of mechanical hardware. 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 the Tandem Mirror Experiment (TMX), Beta II (formerly 2XII-B), and the Mirror Fusion Test Facility (MFTF).

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 Nb_3Sn 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 Magnetic Fusion Engineering Division consists of seven project groups plus a division office. Current work and recent accomplishments of some of these groups are summarized in the following pages.

For further information, contact D.K. Fisher, Ext. 2-6750

Development of High-Field Superconducting Magnets for the Next Generation of Mirror Fusion Research Facilities

One of the major tasks under way in the Magnetic Fusion Engineering Division is the

development of multifilamentary Nb_3Sn high-field conductors. A significant part of this program is the building of a large magnet incorporating the newly developed conductor to generate a field of approximately 12 T. This magnet and its associated equipment have become known as the LLNL High Field Test Facility, since it will be used to demonstrate not only the high-field conductor developed for the mirror program, but also to test conductors developed for possible use in Tokamak toroidal field coil applications.

The magnet windings consist of four outer niobium-titanium sections, which provide a background field of 8 T in a 1-m bore, and two inner sections, wound with the new Nb_3Sn conductor to increase the field to 12 T in the 40-cm bore.

The four outer coils, weighing a total of just over 20 tons, have now been fabricated and tested to full field and current when the total stored magnetic energy is 40 MJ. Figure 1 shows this coil assembly about to be lowered into the 2-m-diam cryostat for testing.

The particle beam development program, funded by the Defense Advanced Research Projects 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.

The development program for the Nb_3Sn conductor was described in the previous Mechanical Engineering Department Technical Review¹; production lengths of this conductor are now being fabricated and winding of these two coils is about to commence.

After winding, the Nb_3Sn coils will be assembled inside the niobium-titanium stack and the whole will be tested as a unit, with its axis vertical in the existing 2-m-diam cryostat. When the facility is used for testing Tokamak development conductors, the two Nb_3Sn coils will be parted in the center and the conductors to be tested will be inserted between them, thus using the facility to provide a background field of approximately 12 T. Since the

FIG. 1. The 8-T, 1-m-bore superconducting magnet ready for lowering in its 2-m-diam cryostat.

stability performance of a pool-boiling conductor is orientation-dependent and since Tokamak toroidal field coils have their axes in the horizontal plane, it will be necessary to use the facility for testing these conductors also with their axes horizontal. This requires a larger cryostat; a 4-m unit has been designed for this purpose and is now out for bid.

The larger magnets and high fields now being built in this development program cannot be accommodated in the existing cryogenic laboratory. A new separate laboratory is, therefore, being built for the sole purpose of developing superconductors and superconducting magnets for the Mirror Fusion Program.

(For further information, contact D.A. Cornish, Ext. 2-6718.)

First Pair of MFTF Magnet Coils Nearing Completion

The mission of the Magnet Systems group for the Mirror Fusion Test Facility (MFTF) is to design, fabricate, and test 22 large superconducting coils for the MFTF. There are two A-cell coils, two Yin-Yang coil pairs, two transition coils, and 14 solenoid coils. When completed, they will constitute the world's largest superconducting coils.

The group's latest work has included completing the winding and inspection of the first pair of Yin-Yang coils and turning them over to a contractor, Chicago Bridge & Iron Company for final welding of the coil case. This work is now nearing completion. The Magnetic Fusion Engineering Division also awarded the largest contract ever let by the Laboratory—\$31 million—to General Dynamics/Convair Division for design and fabrication of the A-cell, transition, and solenoid coils.

Presently, construction on the first Yin-Yang is continuing at a fast pace; operation is scheduled for September 1981 in the Technology Demonstration of the MFTF project. Final work before insertion into the vessel includes helium leak checking of the assembled Yin-Yang coils in their structural case and installing the radiation shields. These radiation shields are comprised of over 300 stainless steel panels and will have liquid nitrogen flowing through them. These panels will be installed on the outside of the structural case by technicians in the Magnet Systems group; the work is expected to take several months.

(For further information, contact T.A. Kozman, Ext. 3-0712.)

Instrumentation Requirements in Planning Stage for the Magnetic Fusion Test Facility

The mission of the Magnetic Fusion Test Facility's (MFTF) Diagnostics Group is to plan, design, and fabricate the plasma diagnostics for the MFTF. The Diagnostics Group is currently supporting the physicists in developing the requirements for the diagnostics instrumentation.

Designing and fabricating the required instrumentation will be carried out in two phases: (1) The "startup set"—the instruments that will be needed in the first few months of operation in 1984; and (2) the "basic set," which will be the additional instruments necessary to complete all the diagnostics measurement goals of the MFTF.

Funding of the startup set will not begin until late in the 1981 fiscal year.

(For further information, contact S.R. Thomas, Jr., Ext. 2-5250.)

Studies of Magnetic Fusion Reactors Point to Commercial-Scale Designs

The ultimate goal of the magnetic fusion program at LLNL is the development of magnetic mirror devices for the economical production of power. Even at this stage in the program (where our experimental devices operate only for short pulses and consume more energy than they produce), we are beginning the design of commercial power-and-fuel-producing reactors. We study these future machines for two reasons: to illuminate the goal and thus give guidance to our current experimental program, and to identify critical technological requirements (for superconducting magnets, for example) which require development.

The reactor studies group is designing reactors based on the two major types of mirror devices: field-reversed mirrors and tandem mirrors. Extensive computer modeling is being used to understand the relationships between the system parameters, while design specialists develop conceptual designs of various system configurations.

Figure 2 is a drawing of a tandem mirror reactor designed to produce about 500 MW of electrical power. The reacting fusion plasma which produces the power is confined to the 56-m-long central cylinder of the reactor. In this central region, a "blanket" surrounds the reacting plasma to absorb

FIG. 2. Engineering concept for the 500-MWe Tandem Mirror Reactor.

the fusion power and to transfer the heat to a turbine-generator plant. Cylindrical magnets surrounding both the plasma and blanket produce a longitudinal magnetic field which prevents the sideways loss of the plasma. The middle two C-shaped magnets (called a Yin-Yang pair) contain a nonreacting plasma whose electrostatic potential reflects the reacting plasma back into the central region.

(For further information, contact G.A. Carlson, Ext. 2-6728.)

Engineering and Construction of the Advanced Test Accelerator is on Schedule

The Advanced Test Accelerator (ATA) group is responsible for designing and constructing a linear induction accelerator with which to empirically study electron beam propagation and to validate the existing theory. Critical propagation ex-

periments will be conducted in various gases and in air to determine the range of beam parameters leading to stable and controllable self-focussed propagation. The accelerator performance characteristics required to conduct these experiments are as follows:

- Current 10 kA
- Energy 50 MeV
- Pulse length 70 ns, FWHM (50 ns flattop)
- Repetition rate 1000 pps max for a 10-pulse burst every 2 s

The accelerator consists of a 2.5-MeV injector and 190 accelerator units, each of which adds 250 keV of energy to the beam. Each of these units has its own pulse power system, accelerator cavity, and magnet system. Clearly, timing and control are critical issues for successful operation.

The ATA program is a vital part of the LLNL Charged Particle Beam Program supported by the Defense Advanced Research Projects Agency through the Naval Surface Weapons Center under the U.S. Department of Defense's Chair Heritage Program.

The ATA program is beginning its third year and is progressing according to the original projections. The main building and other conventional support facilities are well into construction and some are complete. The structural portion of the tunnel that houses the accelerator is complete and backfilling is in process. Shop areas, support power, and fluids systems are being installed. The building to house the power conditioning equipment is scheduled for completion in October 1981.

The accelerator system is designed and most of the components are in various phases of procurement. The Prototype Test Stand is still in operation, providing final information on materials in the pulse power chain which will improve lifetime under high electrical stresses. Testing has demonstrated reliability of all components in the power conditioning chain and in the accelerator by accumulating over 7 million pulses at varying repetition rates. At this point, ATA has achieved the following parameters:

- Full voltage for each module of 250 kV with 10^5 pulses at 350 kV.
- Pulse risetime of less than 20 ns.
- Voltage flattop of 50 ns.
- Pulse width at FWHM of 70 ns.
- Spark gap jitter of less than 1 ns.
- Repetition rate of greater than 1000 pps.

These data provide high confidence that the requisite performance characteristics for the critical experiments will be achieved with flexibility in much of the system for operation at higher levels.

For further information, contact E. W. Pollard, Ext. 2-1474

Synfuels from Fusion: Producing Hydrogen with the Tandem Mirror Reactor and Thermochemical Cycles

This summary examines the technical merits of using a combination of a fusion reactor driver and a thermochemical plant as a means to produce synthetic fuel in the basic form of hydrogen.

Our study covered three major concepts:

- One reactor type—the Tandem Mirror Reactor—advantageously using its simple central cell geometry and its direct electrical output.
- Two reactor blanket module types: a liquid metal cauldron design and a flowing Li_2O solid

microsphere pellet design so as to compare the technology, the thermal-hydraulics, neutronics, and tritium control in a high temperature operating mode (~ 1200 K).

- Three thermochemical cycles—processes in which water is used as a feedstock along with a high temperature heat source to produce H_2 and O_2 . The water-splitting process is a closed-loop sequence of chemical reactions in which the reagents are continuously recycled. The cycles are the General Atomic sulfur-iodine; the Westinghouse sulfur; and the Ispra Joint Research Centre (Ispra, Italy) sulfur-bromine cycles. Only these three cycles, of approximately 30 studied worldwide, have been developed to laboratory model levels and produced demonstration quantities of hydrogen.

The major conclusions from our investigations are as follows:

- We are satisfied that the production of hydrogen using thermochemical cycles has a demonstrated experimental base and potential for commercial exploration.
- There are only three drivers for the processes—(a) the fusion reactor, (b) the HTGR or VHTR, and (c) solar.
- As drivers, the fusion reactor and the HTGR have an edge over solar because the thermochemical cycle cannot be interrupted by diurnal effects.
- Generic fusion reactors and the HTGR are both good candidates for synfuel drivers.
- By fusion reactor type, the TMR has an advantage over the Tokamak, both topologically and due to energy output form.
- The TMR confinement physics for synfuels is substantially the same as it would be for electrical production.

- The key problem in the reactor is designing a high-temperature (1200 K) blanket module

- Particle sintering, extreme temperatures in the zone dividers, and complicated heat transfer preclude the use of the Li_2O pellet design

- The cauldron pool boiler design fares quite well structurally, mechanically, neutronically, for assembly/disassembly, for isolation, for safety by modularization, for low residual activity, as a low stress structure, and as a good module for low tritium inventories and integral tritium production. It requires experimental verification of magnetohydrodynamic effects and energy transfer within the pool.

-For either blanket design, the quantity of process heat delivered to the chemical plant at 1200 K was excellent, approximately 90%.

-Materials problems at 1200 K and in corrosive atmospheres are difficult. However, we are encouraged in having found a set of contemporary materials believed adequate for the temperature environment situations.

-We believe we have introduced an improved design for the SO_3 decomposer—the most difficult unit in the chemical plant—by using a fluidized bed process rather than the packed bed used heretofore.

We conclude that the fusion/synfuel tie is a good one with a high eventual payoff. The problems are difficult but the study is in its infancy. Even during this short study period, we have begun to resolve some of the problems and see possible solutions for others. The program warrants support and we therefore recommend this follow-on work:

1. Exploration of an alternative to the basic cauldron blanket module—the cauldron with heat pipes.

2. The use of dc electricity from the direct converter rather than thermal energy (at $Q > 11$) to Joule heat or ohmically heat the SO_3 decomposer. This may allow relaxation of blanket and transport piping temperatures by several hundred degrees. It also allows reconsideration of the solid Li_2O blanket.

This last step can serve to decrease materials temperature requirements of the blanket, isolate the high temperatures to the SO_3 decomposer unit and decrease the process chemistry complexity of the sulfuric acid section of the process.

The principal investigators in this synthetic fuel study are R. W. Werner of the Magnetic Fusion Engineering Division, and E. L. Ribe. The following are contributors: R. Busch, B. C. Fryer, T. R. Galloway, M. R. Hoffman, O. H. Krikorian, D. S. Rowe, and G. L. Woodruff.

For further information, contact R. W. Werner, Ext. 1290.

The Tandem Mirror Next Step Conceptual Design

The division has begun a study to define the features of an experimental mirror fusion device—the Tandem Mirror Next Step (TMNS)—that will bridge the gap between present

mirror confinement experiments and a power-producing reactor.

The TMX-U and MFTF-B sequence of experiments are expected to provide the plasma physics base needed for the design of a tandem-mirror fusion-power reactor. These experiments, particularly the MFTF-B, will also demonstrate much of the reactor-relevant technology. Optimizing the path between MFTF-B and construction of a demonstration commercial power plant of the mirror type will require a device to bring the physics parameters a final step to the reactor regime and to test and demonstrate all of the technology and engineering appropriate to reactor operation. The purpose of the present study is to develop the features of this "next-step" device in the mirror program, carrying the study through a conceptual design phase.

The TMNS will be a small-scale fusion reactor capable of functioning as an engineering test facility, demonstrating a level of plasma performance and device technology comparable with that of a full-scale demonstration reactor. The TMNS is a steady-state D-T burning tandem mirror with reactor-grade end plugs and solenoid section. Performance guidelines are given in Table I.

The engineering part of the study was organized into three major areas: the nuclear system—systems in the reactor vault; the nuclear auxiliary system—subsystems directly connected to the reactor; and plant facilities—the conventional structures and utilities.

TABLE I. Performance guidelines for the TMNS.

• Steady-state, D-T burning tandem mirror
• Fusion-power density $1 \text{ MW} \cdot \text{m}^{-3}$ Wall loading $0.4 \text{ MW} \cdot \text{m}^{-2}$
• $Q = 5$
• Utility power requirement 250 MW
• Fusion power 200 to 400 MW maximum
• Phased operation, with blanket test and power conversion as add-ons
• Reactor-relevant technology: 12 T superconductor 200 keV neutral beams 100 GHz microwave power
• T_2 handling, T_2 breeding demonstration, remote maintenance system, direct energy conversion

The nuclear system is the most complex and costly of the major systems and therefore was the area of major emphasis in this study. As seen in Fig. 3, the nuclear system consists of three principal units, the two plugs and the central cell.

Starting at the end of the machine and working inward, the first item encountered is the 150-keV high energy pump beam system which fires through openings in the direct converters into the A-cell. The direct converters are arranged to intercept the leakage plasma at the end wall. The main cryopump panels are located parallel to the leakage plasma fan. Straddling the pumping chamber are the arrays of 150-keV medium energy pump beam-lines. These fire through openings in the A-cell magnet structure into the A-cell. The 2-keV low energy pump beams are aimed at right angles to the machine center plane just inside the A-cell magnet. Two sets of FCRH wave guides also terminate in this region. The A-cell magnet forms the barrier well and mirror which provide the stoppering function for the plasma.

Inboard of the A-cell magnets is the plug Yin-Yang coil pair which forms the plug minimum-B field that stabilizes the plasma. The 150-keV plug beam lines (not visible in Fig. 3) are at 45° to the transverse axis of the plug magnets.

Inboard of the plug is the transition magnet which recircularizes the plasma flux tube as it enters the central cell. The central cell is surrounded by the circular solenoidal coils generating the essentially flat field profile for containing the large central cell plasma.

The entire interior of the machine is lined with a cooled neutron shield. The central cell also has space for a "reactor grade" power conversion blanket. The outside of the machine is covered with shielding to absorb any neutrons not captured internally and to shield the reactor vault from gamma rays emitted from neutron-activated internal structures.

The overall length of the machine is nominally 116 m, with 68 m between the Yin-Yang cells. The effective machine length of the center cell is 50.9 m.

The engineering design problems are dominated by the magnets and the neutral beam systems. We have incorporated Nb_3Sn superconductor in the high field regions in anticipation of the successful development of practical conductors for our complex coil shapes. The neutral beams require several new developments including: continuous operation, negative ion sources, and beam purification.

The performance resulting from this design is shown in our power flow diagrams for the TMNS (Figs. 4 and 5). Figure 4 refers to initial machine operation with no thermal or direct energy recovery, while Fig. 5 includes a complete energy recovery and conversion system. We see from Fig. 5 that, with the assumed component efficiencies, it is possible to close the power loop. There is a good basis to believe that the assumed efficiencies can be achieved on the TMNS time scale.

For further information contact J.N. Deegan, P.O. Box 802

1. *Mechanical Engineering Department Technical Review*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. 50016-81-1 (1981), p. 75.

FIG. 3. The nuclear system of the T1NS. Magnet identification numbers are in parentheses, e.g., Yin-Yang magnets (M1, M2).

FIG. 4. Power balance for initial operation with no power conversion. All powers are in megawatts. Fusion power P_{fus} includes power in neutrons P_n and in α -particles P_α . Individual values η are overall conversion efficiencies, and M is the neutron blanket multiplication factor.

FIG. 5. Power balance with full energy recovery and conversion. Symbols are defined in caption for Fig. 4.

MATERIALS FABRICATION DIVISION

The Materials Fabrication Division, a multidisciplinary organization in the Mechanical Engineering Department, provides services that are not available from commercial sources. The number and diversity of LLNL research efforts make this Division one of the Laboratory's largest. We have about 400 highly skilled personnel and more than 3,700 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 for all LLNL programs when requirements call for:

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

In addition, the Division's 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 R. A. Berg, Ext. 2-7643.

American Welding Society Presents Awards to Two Members of the Materials Fabrication Division

Charles E. Witherell, head of MFD's Metal Fabrication Group, was awarded the James F. Lincoln Gold Medal by the American Welding Society for his paper, "Welding Stainless Steels for Structures Operating at Liquid Helium Temperatures." With Terry J. Ramos he was also a co-winner of the Rene D. Wasserman Award, which was presented for their paper, "Laser Brazing." Both awards were made by the Society at its 62nd Annual Meeting in April in Cleveland, Ohio.

Witherell's paper was published in the November 1980 issue of the *Welding Journal*, and was selected by the AWS Awards Committee as "...the

greatest original contribution to the advancement and use of welding in the year 1980." The work described in the paper demonstrated how to make welds in heavy-section stainless steels that could withstand high operating stresses at extremely low temperatures—only a few degrees above absolute zero (-452°F , or 4.2 K).

In studying the behavior of welds at these low temperatures, Witherell observed metallurgical phenomena not evident at warmer temperatures. These gave him clues as to why stainless steel welds often crack under certain conditions. His study took 3 years to complete and led him to formulate a hypothesis for the cause of this cracking, which has plagued the welding industry for some 50 years.

The results of this study, therefore, have a twofold benefit. First, they have demonstrated how to make sound, strong welds that will withstand the rigors imposed upon structures that must withstand supercold environments. This capability is critically needed for equipment that many of the world's promising future sources of energy depend on.

Second, a long-standing welding problem may be well on the way to being solved. Such a solution would improve the reliability of stainless steel welds for literally thousands of applications from power generating plants to fuel tanks for spacecraft.

The paper "Laser Brazing" by Witherell and Ramos was chosen by the AWS Awards Committee as "...the greatest original contribution to the progress and/or advancement of the use of brazing in 1980." Ramos is supervisor of the Laser Metalworking and Process Facility in the MFD.

The procedures developed make it possible for the first time to join metal parts thinner than a human hair with negligible heat input. For many applications involving microparts in the electronics, medicine, and computer fields, ordinary methods of joining metals, like welding and brazing, are too hot and degrade the properties of such ultrathin parts.

In the laser-brazing method, the laser concentrates the heat needed to melt and flow the brazing filler metal (usually an alloy of silver and copper) in the joint. Under the pulsed laser beam, which lasts only 10 ms per pulse, a thin ribbon of the brazing filler metal is melted and wets out across the very narrow gap between the metal being joined, much the way butter wets a frying pan. When the laser beam is switched off the brazing filler metal

solidifies, forming a strong metallic bridge across the parts.

Laminar-Flow Dampers for Stabilizing the Behavior of Pneumatic Vibration Isolators*

During development of the 84-in. diamond turning machine at Lawrence Livermore National Laboratory, we modified a commercially available pneumatic isolator by including a laminar-flow damping system to isolate our precision machine from ground vibration. We developed a configuration of aluminum plates separated by shim stock spacers and substituted this for the usual orifice-flow restrictor for the gas flow in the damping system. This new system gives a leveling response within two seconds and precludes continuous oscillation for the full range of motion amplitudes of interest.

Precision machine tools and measuring machines normally require isolation from ground vibration, with a low natural frequency for the isolator/machine system. But such a "soft mount" could allow the machine to tilt along with its changing load, if there were not also a feedback system or some self-leveling valves to maintain level. The springs that isolate the machine require some damping so that floor motion which occurs at the resonant frequency will not be unduly amplified.

Commercially available isolators employ a pneumatic spring. Damping is provided by dissipating the energy of a compressed gas through a restrictor into an auxiliary volume. An orifice typically joins the two volumes. However, the damping of an orifice is nonlinear, with the resistance increasing with amplitude of motion. Therefore the orifice size chosen is only of optimum damping value for a single amplitude. We found that in a self-leveling system with orifice-damped isolators, some amplitudes of motion have such poor damping that the feedback can render the system unstable.

This problem became evident during development of the 84-in. diamond turning machine being built at LLNL. The machine (Fig. 1) will require fast leveling. The spindle slide on this machine will weigh 10 tons and will move through a distance of 42 in. at speeds up to 15 in./min. Relatively high gain (gas flow in response to change in height) must be employed. When the isolators for the 84-in. machine were first activated, this high gain resulted in a limit cycle (continuous oscillation) of the 80-ton granite base with an amplitude of nearly 0.040 in. Thus vibration isolation became a secondary question until the limit cycle could be corrected.

A control system can be stabilized by a variety of techniques, and in the case of the diamond turning machine, passive damping was sufficient. We achieved this by replacing orifice damping with a laminar-flow restrictor which provides constant resistance to flow throughout the amplitude range of interest.

The restrictor must operate in laminar flow with a Reynolds number below the transition value of 2,000. We found the performance of our devices correlated well with theory when we restricted the flow to values of 500 or less. Capillary tubes were not suitable since they must be excessively long or too great in number to satisfy the joint requirements of optimum flow resistance and low Reynolds number. Parallel plates have worked well, and they can be packaged in a variety of ways. Adequate flow cross section to satisfy the Reynolds number requirement was achieved by stacking plates of aluminum and separating them by shim stock spacers. The spacing chosen is typically in the range of 0.004 to 0.016 in. Figure 2 shows the arrangement of the parallel plates. Figure 3 shows the isolator installed under the machine.

Figure 4 shows the comparison between orifice-flow and laminar-flow damping. With orifice damping, the system oscillates continuously. Data are shown at two locations to indicate the rocking behavior. The oscillation could be stopped by means of low-gain level-sensing valves, but the penalty was a leveling time in excess of 2 min. By contrast, with the laminar flow dampers and high-gain level-sensing valves installed, the transient response to a man stepping on or off the edge of the machine is less than two seconds.

With the oscillation problem under control, the isolators perform well. The vibration level on the 80-ton granite base is less than 1 μ in. in either the

*Dr. Daniel B. DeBra, author of this summary, is a professor of aeronautical and astronautical engineering at Stanford University. The work was performed when he was a summer employee in 1980.

FIG. 1. The newest diamond turning machine being built at Lawrence Livermore National Laboratory will use laminar-flow damping in the pneumatic isolators.

vertical or the horizontal direction. The floor vibration is 10 to 15 $\mu\text{in.}$ at 15 to 22 Hz.

A few pieces of sheet metal and shim stock bolted together and installed inside the isolator have changed the behavior of the isolator system from disastrous to state-of-the-art. In July 1981 we will issue a full report giving the detailed design equations.

The author wishes to acknowledge the assistance of the following members of LLNL's Metrology Group who helped to bring this project to a successful conclusion: Jim Bryan, Don Carter, Dick Clouser, Jim Hamilton, Richard Warner, Chuck Woods, and Art Caraveo.

(For further information, contact J.H. Bryan, Ext. 2-7710.)

Electrochemical Joining of Dissimilar Metals

The chief advantage of joining by plating is that it is done at room temperature, thus eliminating shrinkage stresses and distortions nor-

mally associated with higher temperature joining methods. Another advantage is that properties of component materials do not change. It is an amazingly strong method of joining dissimilar materials.

Although most of the work reported here is the result of experiments performed at Sandia National Laboratories, Livermore, LLNL is contributing to the continued use and expansion of this process.

Joining by plating allows a variety of similar and dissimilar metals and alloys to be joined. Successful joints include aluminum to stainless steel, aluminum to copper, beryllium to beryllium, beryllium to stainless steel, and titanium to titanium. In some cases the joint can be tailored to meet specific design requirements.

Electrochemical joining consists of machining a taper on parts to be joined. Then they are cleaned and mated. The triangular segment between the tapered edges is built up by electroplating before the joint is machined to final tolerance.

Usually parts to be joined are machined with a taper of at least, and preferably greater than,

FIG. 2. Laminar-flow damping is provided by movement of gas along a set of parallel, separated plates.

FIG. 3. The pneumatic isolator will be one of 10 in place under the 84-in. diamond turning machine.

120 deg. Tapers of less than 90 deg should be avoided because planes of weakness, which can cause inferior joints, can form at the junction of crystals growing from the sides of materials being joined. For some applications, such as butt joints, taper machining is not required. In either case, tests should be made to check the extent of taper machining required. After machining, all parts must be cleaned thoroughly to ensure good adhesion of the electrodeposit. The steps involved in electrochemical joining are shown in Fig. 5.

The metal to be electrodeposited as filler should meet two requirements: Metal must plate adherently on materials to be joined, and filler should be of the type that can be deposited in thick, coherent deposits. Materials electrodeposited most frequently are nickel, copper, and nickel-cobalt. Many other metals, including silver, gold, iron, tin, lead, and lead-tin can also be used as filler in electrochemical joining.

A typical electrodeposition rate for nickel and copper is 0.001 in./hr (0.0254 mm/hr), but rates as high as 0.06 in./hr (1.52 mm/hr) are possible. A joint may require up to 0.15 in. (3.8 mm) of electrodeposited filler metal, which would take nearly 150 hr to complete. Obviously, electrochemical joining is not very fast and thus is expensive. However, savings can be achieved because several assemblies may be joined in the same plating bath, thereby reducing the time per assembly.

The strength of a joint made by electroplating depends on the strength of the electrodeposited metal. Nickel-cobalt deposits are considerably stronger than either nickel or copper deposits; tensile strengths range from approximately 60 000 psi (413 MPa) for copper to 210 000 psi (1448 MPa) for nickel-cobalt.

The tensile strength range of various electrodeposits is given in Table 1. If the electrodeposit is the weakest link in the joint, substitution of

FIG. 4. Laminar-flow isolator and level-sensing valves control displacement within 2 s after steps on or off the machine.

TABLE 1. Tensile strength of electrodeposits used for joining.

Metal	Tensile strength, 1000 psi (MPa)
Copper	40-90 (276-620)
Nickel	70-135 (483-931)
Nickel-cobalt	120-220 (827-1517)

nickel-cobalt can improve joint strength notably.

Another way to improve joint strength is to use a sandwich structure consisting of high-strength deposits interspersed with deposits of softer, more ductile metal. For example, a joint in which 0.010-in. (0.25-mm) layers of nickel-cobalt alloy are alternated with deposits of 0.001-in. (0.025-mm) nickel is much tougher than a joint consisting only of nickel-cobalt.

FIG. 5. Five steps in electrochemical joining of copper and aluminum. (Courtesy of Sandia National Laboratories, Livermore.)

Electrochemical joining is confined largely to more exotic structures used in the aerospace and nuclear fields.

The process does not lend itself to large-volume production applications. Some of the material combinations joined by electroplating are listed in Table 2.

Electrochemical joining can be used to join aluminum to solid or hollow round sections of copper or aluminum plate to copper plate. The advantage of electrochemical joining for this metal combination is that resulting joints are more resistant to long-term aging at high temperatures than joints produced by more conventional means. For example, a percussive arc joint at 392°F (473 K) becomes brittle after approximately 1000 to 2000 hr of aging. A cold pressure-welded joint becomes brittle after only 200 to 300 hr of aging. On the other hand, copper electroplated joints between 2024 aluminum and solid copper withstand exposure to 420°F (488 K) for 150 hr without degradation.

Plating can also be used to join unusual shapes. Figures 6 and 7 show two such examples. Figure 6 is an assembly of a 4-in.-diam (101-mm) aluminum sphere joined to an aluminum cylinder of approximately the same diameter.

Electrochemical joining is used to join 39-in. (0.99-mm) rings of 6061-T6 aluminum and AM-363 stainless steel. Figure 7 shows the steps in the process and the finished part. The reason electrochemical joining was chosen for this application is that it is the only method whereby the aluminum retains its T6 condition after joining. Nickel is the electrodeposit.

TABLE 2. Metal combinations joined by electrodepositing.

Metal combination	Electrodeposit
Aluminum to stainless steel	Cu, Ni
Aluminum to copper	Cu
Aluminum to uranium and its alloys	Ni
Beryllium to beryllium	Ni
Beryllium to steel	Ni
Steel to steel	Cu, Ni, Ni-Co
Stainless steel to stainless steel	Ni, Ni-Co
Titanium to titanium	Ni
Titanium to uranium alloys	Ni

FIG. 6. (a) Aluminum sphere joined to aluminum cylinder by plating. In sectioned view (b), note the long taper machined on the cylindrical portion of the assembly. (Photo, courtesy of Sandia National Laboratories, Livermore.)

An amazing demonstration of the strength of a joint made by this process is given by the test to failure of a steel ring (AISI 4340) joined to a high-strength U-Ti ring. Figure 8(a) shows the ring before the compression test. Figure 8(b) shows the failure. Figure 8(c) is the cross section of the failed

FIG. 7. Aluminum and stainless steel rings joined by electrodeposition: (a) steps in the process of joining aluminum to stainless steel; (b) schematic of electroplated joint; (c) a finished part.

wall; note that the failure is outside the joint. The joint was made with 60 Ni—40 Co which has an ultimate strength of 220 000 lb/in.²

(For further information, contact J.W. Dini, Ext. 2-8142.)

(b) 500,000-lb compressive
110,000-lb torque

FIG. 8. Example of a steel uranium joint before and after compression testing to failure [materials are 4340 steel and U-0.75 Ti (high-strength uranium)]; (a) before, (b) after, and (c) joint cross section. (Photo, courtesy of Sandia National Laboratories, Livermore.)

Joining Diamonds to Molybdenum for Diamond Turning

Fastening and shaping diamond gem stones to the end of an industrial tool is a closely held art. Some consider it a trade secret and will not publish on the subject.

Our suppliers produce high quality tools and there was little reason to become involved in the fabrication details. Until now the purchased tools have been quite adequate. The diamonds on these tools are bonded to their shank mechanically, in the same way that a silver filling is bonded to a tooth. There is a limitation, however, on how small the tool can be made because of the necessary depth of the "filling." A new requirement for very small tools has forced us to adopt the brazed-on technique which some manufacturers have been using for the past 15 years. We knew that it was important to match the coefficient of thermal expansion of the shank to that of the diamond to avoid cracking the diamond. Molybdenum is a reasonably close match. Using experience previously developed in the Vacuum Processes Laboratory (VPL), a small diamond was joined to a molybdenum shank by vacuum brazing. Ticusil, a titanium-copper-silver alloy, was used as the braze material. A small piece of 0.002-in. foil was placed under the diamond. The diamond was precisely aligned on the shank and was held in place by a 0.004-in.-diam tungsten spring.

The assembly was placed in a radiation-type vacuum furnace and brazed at a temperature of 900°C. The vacuum was held to 2×10^{-5} Torr. Cool-out was overnight. Figure 9 shows a diamond brazed to a tool shank, one of the first to be bonded here at the Laboratory.

The exact mechanism of the reaction is not fully understood. The titanium apparently reacts with the diamond to form titanium carbide, and the copper-silver reacts with titanium carbide. Titanium melts at 1800°C so it is not yet clear how it can wet the diamond so effectively.

FIG. 9. A diamond brazed to a tool shank.

Ion Plating of 304 Stainless Steel

Preliminary studies of magnetron ion plating of copper on 304 stainless steel were made in MFD's Vacuum Processes Laboratory. The purpose of the study was to determine whether or not the ion plating process, coupled with a magnetron would, in fact, produce a uniform coating that adhered to 304 stainless steel when practical coating rates were achieved. Because this study was the first evaluation to have ever occurred, it concentrated on the relationship of uniformity and adherence rate as a function of pressure. The work to date shows that a deposition rate of about 700 Å/min at the optimum pressure for uniformity and adherence is possible. The coatings were produced in the test apparatus shown in Fig. 10. The chart, Table 3, shows the coating uniformity attained at various pressure levels. There was 100% uniformity, front to back, at both 20 and 27-μm pressure, and at the specific source and substrate voltage levels shown. It should be noted that the 100% uniformity on a cylinder is an indication of uniqueness of this process.

Ring shear tests were performed on a 12.6-mm-diam rod to provide a quantitative means of

(For further information, contact J.B. Bryan, Ext. 2-7710, D.D. Berger, Ext. 2-7684, S.L. Thompson, Ext. 2-8623, or D.L. Carter, Ext. 2-7719.)

FIG. 10. Magnetron ion-plating test cell.

TABLE 3. Uniformity and rate vs pressure.

Pressure (torr)	kVA		Thickness (kÅ)		Uniformity ^a Front/Back
	Source	Substrate	Front	Back	
5	0.350	0.60	35	7.5	21.4%
10	0.300	0.80	20	5	25%
20	0.300	0.80	20	20	100%
27	0.300	0.80	13	13	100%

$$^a \text{Uniformity} = \frac{\text{Back thickness}}{\text{Front thickness}} \times 100$$

measuring adhesion. The ring shear test consists of ion plating a copper ring on the 12.6-mm-diam pin, then increasing the ring thickness by conventional electroplating techniques. This thicker ring now allows a shoulder to be machined on the pin which, in turn, can be conveniently driven off in the fixture shown in Fig. 11(a). The pin configuration prior to insertion into the fixture is shown on Fig. 11(b).

A ring shear test of a coating deposited at optimum rate shows a shear strength of 35 500 psi. As can be seen in Fig. 12, the failure occurred in the copper deposit and not in the ion-plated copper/stainless steel interface. Figure 13 is a load-time curve for the test of the sample shown in Fig. 12.

A summary of this unique work was presented to the American Vacuum Society in Los Angeles on

FIG. 11. (a) Schematic of shearing action. (b) typical ring shear pin.

FIG. 12. Results of ring shear test of magnetron ion plating of copper. Note: failure occurred in the conventional plated copper.

April 21, 1981. The results of the first known experiment of magnetron ion plating have been encouraging—so much so that we are currently trying to coat Ti-6Al-4V with copper by the same process.

For further information, contact: Eric Beall, FAX 214-7684111.

FIG. 13. Ring shear test of ion-plated Cu 304 stainless steel. Failure occurred at 35.5 kpsi (failure mode—Cu/C).

1. J. W. Dini and H. R. Johnson, *Electrochemical Joining: Process, Applications, and Property Data*, SME Technical Paper AD75-855 (1975).
2. J. W. Dini and H. R. Johnson, "A Case History of Joining by Plating Applications," in *SAMPE Quarterly*, Azusa, CA, July 1976.
3. J. W. Dini and H. R. Johnson, "Joining by Electroplating," in *Metals Engineering Quarterly*, Metals Park, O., February 1974.

PUBLICATION ABSTRACTS*

H.P. Alesso, *On the Instabilities of an Externally Loaded Shallow Spherical Shell*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85180 (1980). Prepared for Nuclear Engineering and Design.

The simple von Kármán model of a clamped shallow elastic cap subjected to external pressure is reformulated as an elementary catastrophe. Conceptual understanding of load deflection behavior is substantially improved as a result. Three distinct modes of deflection behavior are identified. One snap-through type behavior is substantiated by comparison to experimental data.

C.M. Bacigalupi and W.A. Burton, *Model Testing of a 1-kg High Explosive Cell Maze*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-53125 (1981).

The basement of the proposed High Explosives Applications Facility (Building 353) at the Lawrence Livermore National Laboratory includes several explosive test cells for the assembly and/or storage of up to 10 kg of high explosive (HE). This document reports 1/8-scale and 1/4-scale model tests conducted to confirm maze design criteria, to determine the cell explosive weight limit based on an allowable 10 psi reflected shock pressure at the hallway-maze doorway, and to specify permissible areas for handling HE within the cell. The integrity of cube-root scaling of the explosive charges detonated in the 1/8-scale model was verified by explosive testing in a comparable 1/4-scale model. Reflected shock pressures in the hallway adjacent to the maze and the effect of HE charge orientation were investigated and are also reported.

T.H. Batzer, R.E. Patrick, and W.R. Call, *A TSTA Compound Cryopump*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84456 (1980). Prepared for the 27th Annual Symp. American Vacuum Soc., Detroit, MI, October 14-17, 1980.

The Tritium System Test Assembly (TSTA) at the Los Alamos National Laboratory is intended to demonstrate realistic fuel supply and cleanup scenarios for future fusion reactors. The vacuum

pumps must be capable of handling large quantities of reactor exhaust gases consisting largely of mixtures of hydrogen and helium isotopes. Cryocondensing pumps will not pump helium at 4.2 K; while cryosorption pumps using molecular sieves or charcoal have good helium pumping speed, the adsorbent clogs with condensed hydrogen while pumping mixtures of both. A solution to this problem is a compound design whereby the first stage condenses the hydrogen species and the second, or sorption, stage pumps the helium. The TSTA pump designed at Lawrence Livermore National Laboratory uses argon gas to cryotrap the helium in the helium-hydrogen mixture. The argon is sprayed directly onto the 4.2 K surface at a rate proportional to the helium flow rate, permitting continuous pumping of the helium-hydrogen mixtures in a single-stage pump. However, the possibility of differential desorption as a first stage in the TSTA gas separation cycle required the inclusion of a first-stage hydrogen isotope condenser. The design, performance, and operating characteristics are discussed.

D.L. Bernreuter and D.H. Chung, *Development of the Seismic Input for Use in the Seismic Safety Margins Research Program*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84197 (1981). Prepared for the 6th Intern. Conf. on Structural Mechanics in Reactor Technology, Paris, France, August 17-21, 1981.

To evaluate the conservatism in present reactor seismic design techniques, a probabilistic based systems model is being constructed. This model will be used to estimate the probability of a seismically induced radioactive release. The systems model requires as input a probabilistic definition of the seismic hazard in suitable form for a site located in the eastern part of the United States. Establishment of the seismic hazard at a site is made in terms of the annual probability of exceeding a given ground motion parameter. Difficulties arise in the probabilistic assessment of seismic input parameters because of the significant uncertainties associated with the earthquake occurrence model and the ground motion model including attenuation relationships. We

*The abstracts are arranged alphabetically by first author's name.

describe an overview of our approach to deal with these uncertainties and evaluate the seismic hazard at a site located in the eastern United States. In particular, we discuss our experience in the use of expert opinion to supplement inadequate data sets to arrive at reliable estimates of exceeding various levels of ground motion. Some examples are provided to illustrate our approach.

D.H. Berwald, J.L. Maniscalco, J.D. Lee, and R.W. Moir, *Fission Suppressed Tandem Mirror Hybrid Reactor Options*, TRW, Inc., Redondo Beach, CA 90278. Prepared for Proc. Fourth ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, King of Prussia, PA, October 14-17, 1980.

The design feasibility of several options for a fission suppressed tandem mirror hybrid reactor blanket are identified but are not ranked. These are based upon two or more radial zones incorporating a nonfission neutron multiplier zone and a fissile fuel (^{233}U) breeding zone. Neutron multiplier options include beryllium, lead, and liquid lithium. Fissile breeding options include thorium metal or oxide packed beds, molten thorium bearing salts, frozen thorium bearing salts, heavy water thorium slurries, and aqueous solutions containing dissolved thorium. Neutronic scoping results for a beryllium and a liquid lithium multiplier option are presented. These are compared with a reference design developed by Lawrence Livermore National Laboratory during 1977.

Bruce M. Boghosian, *Plasma Performance Study for the Tandem Mirror Reactor*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84283 (1980). Prepared for Proc. Fourth ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, King of Prussia, PA October 14-18, 1980.

We have developed a computer code for assessing the performance of new variations on the thermal barrier idea for tandem mirror reactors (TMR's). The code solves the particle and energy balance equations simultaneously for each species of particles in each portion of the machine. The code is thus able to determine the neutral beam and ECRH injection powers that are required to sustain an equilibrium situation, and, from these, to deter-

mine the machine's Q value. This paper focuses on the methodology and numerical algorithms used in accomplishing this solution. We plan to use this code to compare the A-cell barrier TMR with axisymmetric TMR's.

S.E. Bumpus, J.J. Johnson, and P.D. Smith, *Best Estimate vs Evaluation Method Seismic (BE-EMS): An Introduction and Demonstration*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84193 (1981). Prepared for the 6th Intern. Conf. on Structural Mechanics in Reactor Technology, Paris, France, August 17-21, 1981.

The seismic analysis and design of a nuclear power plant requires a significant multidisciplinary effort. This effort requires contributions from specialists in geology and seismology, as well as structural, mechanical, electrical, and foundation engineering. For some time there has been a strong motivation to re-examine the traditional process of seismic analysis in a system context. This motivation arises from a widely held belief that conservatism compound in current designs.

A methodology that will examine the current seismic analysis and design process of nuclear power plants in a system context has been developed in the U.S. NRC Seismic Safety Margins Research Program (SSMRP). However, it is possible to consider only the four elements of the Seismic Methodology Chain (SMC)—seismic input, soil-structure interaction, major structure response, and subsystem response, in a coupled or system fashion. The quantities of interest are then response parameters.

The term Best Estimate vs. Evaluation Method was introduced to identify this simplification. The objective is to compare two seismic analysis procedures. One comparison could be between a "Best Estimate" Method (BE) and an "Evaluation" or Standard Review Plan-like "Method" (EM) for "Seismic" (S) analysis and design. Hence, the abbreviation BE-EMS. However, comparisons are not limited to BE versus EM—any two methodologies may be compared.

A demonstration of the BE-EMS concept is presented. The example considered in this study links two elements of the SMC—seismic input and structural response. The EM procedure was composed of synthetic time histories generated to meet

the design criteria of U.S. NRC Regulatory Guide 1.60, the square-root-of-the-sum-of-the-squares (SRSS) rule of combination for response due to three components of motion, and broadening of in-structure response spectra to account for uncertainties in the dynamic characteristics of structures. Corresponding elements in the BE procedure were recorded time histories—three components with recorded phasing, and probability distributions on structural dynamic characteristics which were sampled repetitively to incorporate structural uncertainties directly.

Two quantities were used in the comparison of BE and EM response. Factors of Comparison (FOC) were computed as the quotient of the mean EM response spectra and the mean BE response spectra. In addition, Probabilities of Exceedance (POE) were computed representing the probability of a BE response exceeding the corresponding EM response. Both the FOC and POE vary over the frequency range of interest. The results demonstrated the apparent conservatism of the EM design criteria subject to the assumptions of the study.

Gustav A. Carlson, *The Design of Tandem Mirror Reactors with Thermal Barriers*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84518 (1980). Prepared for Proc. Fourth ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, King of Prussia, PA, October 14-17, 1980.

In a tandem mirror fusion reactor, the fusion power is produced in the straight cylindrical central cell. The central-cell magnets are low-field solenoids. Because the central-cell plasma is near or at ignition, no plasma heating hardware is required for the central cell. A basic design philosophy for the central cell is that of axial modularity, and a number of different module designs have been proposed which lend themselves to mass-production techniques.

Axial confinement of the central-cell fusion plasma is enhanced by the electrostatic potential of the plug plasmas. The incorporation of thermal barriers (regions of depressed potential between the central cell and plug plasmas) allows the confining potential to be created partly by an elevated plug electron temperature instead of solely by a higher plug density. A number of different thermal barrier

configurations have been proposed, and are now under comparative study. A primary concern is the determination of magnetic field shapes that will ensure magnetohydrodynamic (MHD) stability at high central-cell β .

End-plug technologies for tandem mirror reactors include high-field superconducting magnets, neutral beam injectors, and gyrotrons for electron cyclotron resonant heating (ECRH). In addition to their normal use for sustenance of the end-plug plasmas, neutral beam injectors are used for "pumping" trapped ions from the thermal barrier regions by charge exchange. An extra function of the axially directed pump beams is the removal of thermalized alpha particles from the reactor. The principles of tandem mirror operation with thermal barriers will be demonstrated in the upgrade of the Tandem Mirror Experiment (TMX-U) in 1981 and the tandem configuration of the Mirror Fusion Test Facility (MFTF-B) in 1984. Continued analysis and conceptual design over this period will evolve the optimal configuration and parameters for a power producing reactor.

G.A. Carlson and W.S. Neef, Jr., *Tandem Mirror Reactor Studies at Lawrence Livermore National Laboratory*, FY 1980. Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCID-18989 (1981).

The principles of tandem mirror operation with thermal barriers will be demonstrated in the upgrade of the Tandem Mirror Experiment (TMX-U) in 1981 and the tandem configuration of the Mirror Fusion Test Facility (MFTF-B) in 1984. Continued analysis and conceptual design over this period will evolve the optimal configuration and parameters for a power-producing reactor. In this article we describe the progress we have made in this reactor design study effort during 1980.

In our concept of a tandem mirror fusion reactor, the fusion power will be produced in the straight, cylindrical central cell. The central-cell magnets are low-field solenoids. Because the central-cell plasma is near or at ignition, no plasma-heating hardware is required for the central cell. A basic design philosophy for the central cell is that of axial modularity, and a number of different module designs have been proposed which lend themselves to mass-production techniques.

Axial confinement of the central-cell fusion plasma is enhanced by the electrostatic potential of the end plug plasmas. The incorporation of thermal barriers (regions of depressed potential between the central-cell and plug plasmas) allows the confining potential to be created partly by an elevated plug electron temperature instead of solely by a higher plug density. The rapidly evolving knowledge concerning tandem mirrors with thermal barriers has resulted in a number of alternative end-plug configurations. Each of these configurations is different in its approach to obtaining magnetohydrodynamic (MHD) stability at high values of central-cell plasma pressure, which is essential for the achievement of economically high fusion power density. MHD stability in a tandem mirror requires a proper balance between good magnetic field line curvature (concave outward) and bad magnetic field line curvature (concave inward). The investigation and comparison of these different end plugs are the principal present efforts in our study of tandem mirror reactors.

End-plug technologies for tandem mirror reactors include high-field superconducting magnets, neutral-beam injectors, and gyrotrons for electron cyclotron resonant heating (ECRH). In addition to their normal use for sustenance of the end-plug plasmas, neutral-beam injectors are used for "pumping" trapped ions from the thermal barrier regions by charge exchange. An extra function of the axially directed pump beams is the removal of thermalized alpha particles from the reactor.

D.W. Coats, R.C. Murray, and D.L. Bernreuter, *Methods for Developing Seismic and Extreme Wind Hazard Models for Evaluating Critical Structures and Equipment at U.S. Department of Energy Facilities and Commercial Plutonium Facilities in the United States*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85459 (1981). Prepared for the 6th Intern. Conf. on Structural Mechanics in Reactor Technology, Paris, France, August 17-21, 1981.

Lawrence Livermore National Laboratory (LLNL) is developing seismic and wind hazard models for the U.S. Department of Energy (DOE). The work is part of a three-phase effort to establish building design criteria developed with a uniform methodology for seismic and wind hazards at the various DOE sites throughout the United States. In

Phase 1, LLNL gathered information on the sites and their critical facilities, including nuclear reactors, fuel-reprocessing plants, high-level waste storage and treatment facilities, and special nuclear material facilities. Phase 2—development of seismic and wind hazard models—is discussed in this paper, which summarizes the methodologies used by seismic and extreme-wind experts and gives sample hazard curves for the first sites to be modeled. These hazard models express the annual probability that the site will experience an earthquake (or windspeed) greater than some specified magnitude. In the final phase, the DOE will use the hazards models and LLNL-recommended uniform design criteria to evaluate critical facilities. The methodology presented in this paper also was used for a related LLNL study—involving the seismic assessment of six commercial plutonium fabrication plants licensed by the U.S. Nuclear Regulatory Commission (NRC).

C.A. Cornell, M.K. Ravindra, and C.K. Chou, *Development of Load Combinations for Design of Nuclear Component - Probabilistic Methodology*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84184 (1981). Prepared for the 6th Intern. Conf. on Structural Mechanics in Reactor Technology, Paris, France, August 17-21, 1981.

Procedures are described for the evaluation of reliabilities implied by current component design criteria and for the systematic derivation of design criteria that achieve specified target component reliabilities. The proposed method of calculating the limit state probability, P_f , of a component considers the uncertainties of load processes and component resistances. The probability distribution of the extreme combined response is developed by convolving probability distributions of static responses with the extreme of the combined time varying dynamic responses. The latter distribution is conservatively approximated by a method which makes use of the mean upcrossing rate (as functions of the response level) and the arbitrary-point-in-time probability density functions of the individual responses. The probability of the component reaching a limit state is the probability that the combined maximum response exceeds the component resistance. A representative sample of components designed in accordance with a set of design criteria will have a

frequency distribution of P_F that represents the limit state probability implied by the criteria set. This technique of reliability evaluation of design criteria can be used to place a new load and/or a new load combination in the proper service level category.

The design criteria are derived such that the components of a particular class have approximately the same limit state probabilities. The Load and Resistance Factor design (LRFD) format, equation (18), which is a generic form of most current mechanical and structural design criteria is selected as appropriate for load combination methodology development. The load and resistance factors are selected using an optimization procedure wherein a function of the difference between P_F and the target limit state probability, P_T , is minimized over the class of components.

D.N. Cornish, *Superconductivity and Cryogenics for Mirror Fusion*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-83916 (1980).

A brief introduction to the mainline experiments being presently pursued in mirror fusion research is followed by a more detailed description of the cryogenic and superconductive aspects of the Mirror Fusion Test Facility (MFTF) and its extension to a tandem machine. The large volume of magnetic field required for confinement has a maximum intensity of close to 8 T and is produced by a variety of superconducting magnets. A large and complex cryogenic system is necessary to provide the 4-K environment for these coils and to meet the large cryopumping needs of the machine.

C.C. Damm, J.N. Doggett, R.H. Bulmer, W.S. Neef, G.W. Hamilton, A.E. Sherwood, S. Szybalski, B.M. Boghosian, G.A. Carlson, R.W. Moir, W.L. Barr, J.L. Erickson, R.W. Devoto, T.H. Batzer, and C.L. Hanson, *Preliminary Design of a Tandem-Mirror-Next-Step Facility*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-53060 (1980).

The Tandem-Mirror-Next-Step (TMNS) facility is designed to demonstrate the engineering feasibility of a tandem-mirror reactor. The facility is based on a deuterium-tritium (D-T) burning, tandem-mirror device with a fusion power output of 245 MW. The fusion power density in the central

cell is 2.1 MW/m^3 , with a resultant neutron wall loading of 0.5 MW/m^2 . Overall machine length is 116 m, and the effective central-cell length is 50.9 m. The magnet system includes end cells with Yin-Yang magnets to provide magnetohydrodynamic (MHD) stability and thermal-barrier cells to help achieve a plasma Q of 4.7 (where Q = fusion power/injected power). Neutral beams at energies up to 200 keV are used for plasma heating, fueling, and barrier pumping. Electron cyclotron resonant heating at 50 and 100 GHz is used to control the electron temperature in the barriers. Based on the resulting engineering design, the overall cost of the facility is estimated to be just under \$1 billion. Unresolved physics issues include central-cell β -limits against MHD ballooning modes (the assumed reference value of β exceeds the current theory-derived limit), and the removal of thermalized α -particles from the plasma.

John L. Erickson, Irving U. Ojalvo, and John O. Myall, *Structural Support of a Yin-Yang Magnet for a Tandem Mirror Reactor with Thermal Barriers*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84234 (1980).

Conceptual designs of mirror power reactors have historically used high-field magnets that required massive restraining structures, in addition to the basic coil case, to support the electromagnetic loads. Recently, application of the thermal barrier concept to tandem mirrors has sufficiently improved reactor performance such that a Yin-Yang reactor magnet may not require significantly higher technology than is required for the Mirror Fusion Test Facility (MFTF) Yin-Yang coils. The approach taken in our study was to use a simple coil case of compact design and to add and modify structural members to transfer loads from one coil to the other. It has been assumed that the magnet assembly will resemble the MFTF design. The structural material selected is 304 LN stainless steel with a yield stress of 120 ksi at 4 K. The niobium-titanium conductor is assumed to be of square cross-section to allow winding in two planes. This report contains a comprehensive summary covering work performed by Grumman Aerospace Corporation, in conjunction with the Lawrence Livermore National Laboratory, on the TMP Yin-Yang coils. The Yin-Yang coil pair used for our analysis has a major arc radius of 2.7 m and a minor arc radius of

1.18 m, compared with 2.5 m and 0.75 m for the MFTF. The maximum field on the present conductor is 9.05 T. This magnetic field is created by, and interacts with, a conductor current which produces a 360 million Newton total force, tending to separate the parallel lobes of the major arcs.

A. Goldberg, S.L. Albertson, and Irene A. Fedrick, *Characterization and Evaluation of a Turbine Disc Section Containing a Service Crack*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCID-18699 (1981).

Cracking had occurred in the keyway of a low-pressure turbine disc. We evaluated a section of the disc to determine whether the tensile and Charpy V-notch (CVN) toughness properties in the hub region corresponded to those originally specified for this disc. We also characterized the microstructure of the steel and analyzed the bore surface. Room-temperature tensile properties and $FATT_{50}$ were found to be essentially unchanged from the specified values. The steel was relatively clean. However, excessive segregation was present and was reflected by variations in grain size, microhardness, sulfur distribution, and inclusion content. Using x-ray analysis, we identified the presence of an MoS_2 deposit and an $FeCr_2O_4$ corrosion film along the bore. We propose that excessive segregation (inclusions, alloying elements, embrittling constituents) contributes to excessive scatter in our CVN results. Segregation and MoS_2 lubricant may both contribute to the cracking problem.

L.G. Green, E. James, E.L. Lee, E.S. Chambers, C.M. Tarver, C. Westmoreland, A.M. Weston, and B. Brown, *Delayed Detonation in Propellants from Low Velocity Impact*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84999 (1981). Prepared for the 7th Symp. (Intern.) on Detonation, Annapolis, MD, June 16-19, 1981.

Certain high HMX-content propellants are found to undergo delayed detonation when cylinders of the propellant are subjected to axisymmetric impact. The magnitude of the impact pressure is considerably less than that required for prompt shock initiation. It is also found that granular propellant (65-78% theoretical maximum density) packed in a thick-walled (50 mm) Plexiglas pipe is easily detonated by relatively low-velocity (130 m/s)

piston compaction of the porous propellant. The above processes appear to be related to each other and to the more classical deflagration-to-detonation studies carried out in heavy-walled pipes where the explosive is deliberately ignited to start the build-up to detonation.

R.S. Hawke and A.L. Brooks (LLNL), and C.M. Fowler and D.R. Peterson (Los Alamos), *Electromagnetic Railgun Launchers: Space Propulsion Applications*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85007 (1981). Prepared for AIAA/JSASS/DGLR 15th Intern. Electric Propulsion Conf., Las Vegas, NV, April 21-23, 1981.

Considerable progress in understanding railgun operation, requirements, and limitations has been made. It appears that railguns may have potential application to space propulsion and direct launch. This paper discusses the state of the art and expected capability of railgun systems. It includes the requirements and an example design of an earth-based system capable of launching projectiles through the atmosphere at velocities greater than 8 km/s. The critical issues and problem areas that require investigation are described.

C.D. Henning, *The Economic Potential of Magnetic Fusion Energy*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84938 (1981).

Fusion energy is a virtually inexhaustible resource in which light nuclei fuse to produce heavier nuclei and energy, as evidenced by radiation from the sun and the stars. While many exothermic reactors are possible, the most accessible operating conditions are found for a deuterium and tritium mixture. As a later development, pure deuterium fuels in high temperature mirror reactors might obviate the need to breed tritium, or perhaps a deuterium-helium III cycle could be used to eliminate most of the reaction neutrons and induced radioactivity in surrounding structures. Scientific feasibility of magnetic fusion is no longer seriously in doubt. Rapid advances have been made in both Tokamak and mirror research, leading to a demonstration in the TFTR Tokamak at Princeton in 1982 and the tandem mirror MFTF-B at Livermore in 1985. Accordingly, the basis is established

for an aggressive engineering thrust to develop a reactor within this century. However, care must be taken to guide the fusion program towards an economically and environmentally viable goal. While the fusion fuels are essentially free, capital costs of reactors appear to be at least as large as current power plants. Accordingly, the price of electricity will not decline, and capital availability for reactor constructions will be important. Details of reactor cost projections are discussed and mechanisms suggested for fusion power implementation. Also discussed are some environmental and safety aspects of magnetic fusion.

C.D. Henning, A.J. Hodges, J.H. VanSant, E.N. Daldor, R.E. Hinkle, J.A. Horvath, R.M. Scanlan, D.W. Shimer, R.W. Baldi, and R.E. Tatro, *Mirror Fusion Test Facility Magnet System—Final Design Report*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-52955 (1980).

The Mirror Fusion Test Facility (MFTF) is the largest of the mirror program experiments for magnetic fusion energy. It seeks to combine and extend the near-classical plasma confinement achieved in 2XIIB with the most advanced neutral beam and magnet technologies available. The product of ion density and confinement time will be improved while the superconducting magnet weight will be extrapolated from 15 tons in Baseball II to 375 tons in MFTF. Other project parameters show that the MFTF will traverse much of the distance in magnet technology towards the reactor regime. Authorized to start construction in FY 1978, the MFTF project is close to its schedule for completion in October 1981. Following a change in geometry at the end of the preliminary design stage, detailed design was commenced in May 1978. By August of 1979 the design was complete and the first coil constructed. The second coil was finished in March 1980. Final assembly, including the case structure, will be completed and ready for testing in early 1981. An extension of the project called MFTF-B has been authorized and will delay project completion three years.

R.W. Hoard, R.M. Scanlan, G.S. Smith, and C.L. Farrell, *The Effect of Strain on the Martensitic Phase Transition in Superconducting Nb₃Sn*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84211 (1980).

The connection between the cubic-to-tetragonal martensitic phase transformation and the phenomenon of superconductivity in AlS compounds is being investigated. The degradation of the critical parameters, such as T_c , H_{c2} , and J_c , with mechanical straining is of particular interest. Since martensitic transitions are also known to be strain sensitive, perhaps the structural change is directly responsible for the reduction in superconducting properties. We performed low-temperature x-ray diffraction experiments on Nb₃Sn ribbons (with the bronze layers etched off) mounted on copper and indium sample stages. The cryostat we used is unique in that it has a vacuum mechanical insert which allows the superconductor to be placed under both compressive and tensile strains while at low temperatures. Preliminary results indicate that the martensitic phase transition temperature T_m increases with compressive strains. Other effects of strain on tetragonal phase production are also discussed.

J.J. Johnson, G.L. Goudreau, S.E. Bumpus, O.R. Maslenikov, T.Y. Chuang, T.Y. Lo, B.J. Benda, and P.D. Smith, *Seismic Response Calculations for the U.S. NRC Seismic Safety Margins Research Program*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84194 (1981). Prepared for the 6th Intern. Conf. on Structural Mechanics in Reactor Technology, Paris, France, August 17-21, 1981.

The seismic analysis and design of a nuclear power plant requires contributions from specialists in geology and seismology, as well as structural, mechanical, electrical, and foundation engineering. For some time there has been a strong motivation to re-examine the traditional process of seismic analysis in a system context. This motivation arises from a widely held belief that conservatism compound in current designs. That is, at each stage, conservatisms are introduced to account for uncertainties, and these conservatisms compound from one stage to the next. Presently, only minimal compounding emphasis is placed on this because the conservatisms are not quantified.

A methodology that will examine the current seismic analysis and design process of nuclear power plants in a system context was developed in the U.S. NRC Seismic Safety Margins Research Program (SSMRP). Examining the total plant, in-

cluding the functional requirements of operating and safety systems and their interdependence, is the most complete manner of addressing the various issues, and this is the SSMRP approach. The systems analysis approach encompasses the entire Seismic Methodology Chain (SMC), the systematic representation of the nuclear power station's reactor systems using event/fault tree methodology, a description of the fragility of structures, components, and systems due to seismic loading conditions, and a computational approach which computes the probability of failure of structures, components, and systems and the probability of radioactive releases. This report describes the methodology used in the SSMRP to determine the seismic responses and their variability to be input to the systems analysis program SEISIM.

The computer program SMACS (Seismic Methodology Analysis Chain with Statistics) was developed to link together the seismic input, soil-structure interaction (SSI), major structure response, and subsystem response calculations. The response determined with SMACS is the input to SEISIM. Hence, a compatibility between the responses and the fragility descriptions of structures, components, and systems must be maintained.

The SSMRP response calculations should be as realistic as possible and uncertainties should be modeled using probabilistic methods. Best estimate models of the entire SMC were used. Uncertainty in each phase was incorporated as follows: In the seismic input, the largest source of variability was incorporated through ensembles of time histories; in the SSI phase, the mechanism to include variability was the shear modulus and damping in the soil; in the structures and subsystems stages, variations in the frequencies and modal damping properties were the mechanism. These variations were treated in SMACS. Next, the response calculations must be performed for a range of excitation levels reflecting the fact that the systems analysis yields the probability of failure and radioactive release for the earthquake hazard which includes earthquakes of small amplitude up to very large events.

This report presents a summary of seismic response calculations for SSMRP Phase I including input parameters, their variability, and results of the calculations.

J.F. Lee, D.L. Chapin, and J.W.H. Chi, *Parametric Systems Analysis for Tandem Mirror Hybrids*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84248 (1980). Prepared for Proc. Fourth ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, King of Prussia, PA, October 14-17, 1980.

Fusion fission systems consisting of fissile producing fusion hybrids combining a tandem mirror fusion driver with various blanket types and net fissile consuming LWR's have been modeled and analyzed parametrically. Analysis to date indicates that hybrids can be competitive with mined uranium when U_3O_8 cost is about 100 \$/lb, adding less than 25% to present-day cost of power from LWR's. Of the three blanket types considered [uranium fast fission (UFF), thorium fast fission (ThFF), and thorium fission suppressed (ThFS)] the ThFS blanket has a modest economic advantage under most conditions but has higher support ratios and potential safety advantages under all conditions. Uncertainties in tandem mirror modeling caused about a factor of 2.5 swing above and below the nominal fissile costs (120 to 20 \$/g- ^{235}U with the ThFS blanket), which in turn results in less than a 20% swing in electricity cost (54 to 39 mills/kW·he).

J.D. Lee, R.A. Engholm, D.J. Dudziak, and R.C. Haight, *Fusion Reactor Nucleonics: Status and Needs*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84574 (1980). Prepared for Proc. Fourth ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, King of Prussia, PA, October 14-17, 1980.

The national fusion technology effort has made a good start at addressing the basic nucleonics issues, but only a start. No fundamental nucleonics issues are seen as insurmountable barriers to the development of commercial fusion power. To date the fusion nucleonics effort has relied almost exclusively on other programs for nuclear data and codes. But as we progress through and beyond Engineering Test Facility (ETF) type design studies, the fusion program will need to support a broad-based nucleonics effort including code development, sensitivity studies, integral experiments, etc.

acquisition, etc. It is clear that nucleonics issues are extremely important to fusion development and that we have only scratched the surface.

J.D. Lee and R.W. Moir, *Fission-Suppressed Blankets for Fissile Fuel Breeding Fusion Reactors*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84104 (1980). Prepared for the Journal of Fusion Energy.

Two blanket concepts for DT fusion reactors are presented which maximize fissile fuel production while at the same time they suppress fission reactions. By suppressing fission reactions the reactor will be less hazardous, and therefore easier to design, develop, and license. Also, by suppressing fission reactions, such a fusion breeder operating at a given nuclear power level can produce much more fissile fuel. The two blankets described both use beryllium (Be) for neutron multiplication. One uses two separate circulating molten salts: one salt for tritium breeding, the other for ^{235}U breeding; the second uses separate solid forms of lithium and thorium for breeding and is helium-cooled.

O.R. Maslennikov, J.C. Chen, and J.J. Johnson, *Uncertainty in Soil-Structure Interaction Analysis of a Nuclear Power Plant: A Comparison of Two Analysis Procedures*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85702 (1981). Prepared for the 6th Intern. Conf. on Structural Mechanics in Reactor Technology, Paris, France, August 17-21, 1981.

Predicting the seismic response of stiff, massive structures, such as those found at a nuclear power plant, accounting for the effect of soil-structure interaction (SSI), is subject to a number of uncertainties. A principal source of uncertainty comes from differences in SSI analysis techniques. This uncertainty and, in particular, the idealization of the soil-structure system, is the subject of this discussion.

The study from which the material discussed herein is taken is part of the U.S. NRC Seismic Safety Margins Research Program (SSMRP). The SSMRP is developing probabilistic methods that more realistically estimate the behavior of nuclear power plants during earthquakes. A demonstration of the SSMRP methodology is being performed on the Zion nuclear power station in Zion, Illinois, USA. The plant consists of two NSSS units with a

power rating of 1100MW(e) each. In terms of SSI, three basic structures exist—two reactor containment buildings, each with its own foundation, and the auxiliary, fuel handling, and turbine generator building complex supported on a foundation of varying elevation and thickness. The latter complex is also tied together by continuous slabs and walls in the upper stories. The SSI analysis of the complete Zion nuclear power plant is the subject of the present study; the discussion of this paper is limited to one aspect of the study—the analysis of a single isolated reactor building.

Two alternative techniques were applied. The first was a linear finite element approach using the computer program FLUSH. The significant dynamic characteristics of the structures were modeled by sets of single degree-of-freedom models with appropriate mass, stiffness, and damping characteristics. Response was obtained at the basemat level of the FLUSH model. A second stage structural analysis was performed to compute detailed structural response. The second method was a substructure approach using the computer program CLASSI, which is, in general, three-dimensional and permits detailed structural models to be incorporated into the analysis. The dynamic characteristics of the reactor building structures were represented by their modal properties, and SSI effects were included as foundation input motions and impedances for an axisymmetric embedded foundation.

Basemat and in-structure response at selected points were obtained from the FLUSH and CLASSI analyses in the form of peak values and response spectra. The results compared very well with differences in peak values generally averaging about five percent and spectral amplitude variations of less than thirty percent. A comparison of results from second stage analyses which omitted the basemat rocking component showed that significant shifts in frequencies of spectral peaks occurred and that, in general, the effect of omitting rocking cannot be predicted. The problem studied herein represents a very simple one in terms of differences in assumptions made for the CLASSI and FLUSH analyses. More complicated problems involving complex structures and multiple foundations are the subject of the remainder of the study and are expected to result in much greater variations between the two methods.

E.W. McCauley, H.J. Weaver, and T.J. Altenbach, *A Method for Chug Classification*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85707 (1981). Prepared for the 1st Intern. Specialists Meeting on BWR-Pressure Suppression Containment Technology, GKSS Research Center, Geesthacht, Federal Republic of Germany, June 1-3, 1981.

A method is presented which classifies the late time condensation phenomena of chugging as it occurs in pressure suppression tests. The method uses a five (5) character letter code which describes both the spectral (frequency) and temporal characteristics of a chug event.

R.C. Murray, T.A. Nelson, D.W. Coats, D.S. Ng, and H.J. Weaver, *Impact of the January-February 1980 Earthquake Sequence on Various Structures at the Lawrence Livermore National Laboratory*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85460 (1981). Prepared for the 6th Intern. Conf. on Structural Mechanics in Reactor Technology, Paris, France, August 17-21, 1981.

On January 24, 1980, California's Livermore Valley was rocked by a moderate earthquake that caused some damage to the Lawrence Livermore National Laboratory (LLNL). The earthquake, which measured 5.5 on the Richter scale and was centered about 20 km (12 mi) northwest of the Laboratory, produced estimated peak horizontal ground acceleration at LLNL of between 0.15 and 0.3 g. The earthquake was part of a sequence that included two sharp aftershocks (magnitudes 5.2 and 4.2) within 1.5 minutes of the initial event. A second earthquake (magnitude 5.8) struck on January 26, and several lesser earthquakes occurred during the next few weeks.

Damage resulted primarily from the January 24 earthquake with estimates of its impact ranging upward to \$15 million, including \$3 million in direct damage and \$12 million in upgrading costs. Five facilities that house appreciable amounts of radioactive materials suffered essentially no structural damage, while conventional structures were damaged. This difference reflects differences in design criteria.

This paper describes the damage impact of the January 24 earthquake, including:

- Background information on LLNL.
- Discussion of pre-earthquake seismic safety philosophy.
- Description of the impact of the January 24 earthquake, including a description of the seismic setting of the Laboratory, a discussion of the ground motion, and a summary of damage.

This paper also describes a data gathering and reduction effort at LLNL in the aftermath of the January earthquakes. In anticipation of additional aftershocks, several buildings and structures were equipped with devices to monitor building response. Data were recorded for both the February 12 and 21 aftershocks, which measured 2.6 on the Richter scale. The data were primarily used to determine peak accelerations; however, we also used computer programs developed at LLNL to extract information about the structural dynamic behavior from velocity time-history signals. An analysis of one building is presented to show the usefulness of the technique in identifying the principal vibratory modes of a structure and the frequencies and damping values of these modes. The potential of this technique for monitoring changes in the seismic vulnerability of critical structures is discussed.

Paul D. Smith and Richard G. Dong, *Seismic Safety Margins Research Program (Phase I) Interim Definition of Terms*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-53001 (1980).

The Seismic Safety Margins Research Program (SSMRP) examines the seismic analysis and design process of nuclear power plants in a systems approach. The seismic analysis and design of a nuclear power plant requires a significant multidisciplinary effort. This effort requires contributions from specialists in geology, seismology, and structural, mechanical, electrical and foundation engineering. For some time there has been a strong motivation to reexamine the traditional process of seismic analysis in a systems context. This motivation arises principally from a widely held belief that conservatism compound in current designs. That is, at each stage, conservatisms are introduced to account for uncertainties, and these conservatisms compound from one stage to the next. Presently, only minimal compensations for compounding are made in each stage because the conservatisms are not quantified. The result may be an over-conservative seismic design.

The objectives of the Seismic Safety Margins Research Program (SSMRP) are to estimate the degree of conservatism of the present Standard Review Plan (SRP) seismic safety requirements, and to develop improved requirements and methods for safety assessment.

Richard W. Werner, *The Tandem Mirror Reactor as a Synthetic Fuel Producer*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-83536 (1980) Prepared for Proc. Fourth ANS Topical Meeting on The Technology of Controlled Nuclear Fusion, King of Prussia, PA, October 14-17, 1980.

We believe that fusion should and must play as strong a role in the production of fuels and chemical feedstocks as it is expected to play in the production of electricity. The role, in fact, may be even stronger since the production of fuel in the form of hydrogen, hydrocarbons, and their derivatives useful for transportation, industrial processes, or for residential and commercial use or the production of chemicals based on hydrogen or hydrocarbons is three times as high in the United States as is the use of energy for the production of electricity. We further believe that fuel production is not inimical to electricity production from fusion but is complementary to it and strengthens the base of the

entire fusion program. We report on a scoping design of a fusion reactor based on tandem mirror physics coupled to thermochemical processes for the production of hydrogen.

J.P. Zhasnik, D.N. Cornish, R.M. Scanlan, A.M. Jewell, R.L. Leber, A.R. Rosdahl, and M.R. Chaplin, *Background Field Coils for the High Field Test Facility*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-85073 (1981).

The High Field Test Facility (HFTF), presently under construction at LLNL, is a set of superconducting coils that will be used to test 1-m-o.d. coils of prototype conductors for fusion magnets in fields up to 12 T. The facility consists of two concentric sets of coils; the outer set is a stack of Nb-Ti solenoids, and the inner set is a pair of solenoids made of cryogenically stabilized, multifilamentary Nb₃Sn magnets. The HFTF system is designed to be parted along the midplane to allow high-field conductors, under development for Tokamak fusion machines, to be inserted and tested. The background field coils were wound pancake-fashion, with cold-welded joints at both the inner and outer diameters. Turn-to-turn insulation was fabricated at LLNL from epoxy-fiberglass strip. The coils were assembled and tested in our 2-m-diam cryostat to verify their operation.