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UCRL-52000-76-10

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Energy and Technology Review

OCT. 1976

Prepared for U S. Energy Research & Development
Administration under Contract No. W-7405-Eng-48

STACK EMISSION STUDY

LAWRENCE
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Printed in the United States of America
Available from
National Technical Information Service
U.S. *Department of Commerce*
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $; Microfiche $2.25

Page Range	Domestic Price
001-025	$3.50
026-050	$4.00

Distribution Category UC-2

Energy and Technology Review

UCRL-52000-76-10
OCTOBER 1976

Scientific Editor: Robert W. Selden
General Editors: Richard B. Crawford
Kent L. Cummings
Judyth K. Prono

ABOUT THE COVER

The 90-m stack serving a generating unit equipped with a wet venturi scrubber for emission control at a western U.S. coal-fired power plant. The white plume is composed of water droplets that quickly evaporate; the streaky discoloration is caused by acidic condensation from the plume. Although scrubber-equipped units like this one have much cleaner-looking plumes than those emitted from precipitator-equipped units, our studies show that their emissions are more likely to deposit toxic elements in the lungs.

ENVIRONMENT, HEALTH AND SAFETY

SCIENCE AND TECHNOLOGY

MASTER

LAWRENCE LIVERMORE LABORATORY
University of California
Livermore, California 94550

Briefs

The short items on this page announce recent developments of importance. Some of these items may be amplified in future issues; none of this material is reported elsewhere in this issue.

WALKER LAKE: POSSIBLE NEW URANIUM RESOURCE

For ERDA's National Uranium Resource Evaluation (NURE), we have identified a possible new uranium resource in Walker Lake, western Nevada. Some 550 tonnes of uranium are dissolved in the lake, which lies about 80 km east-southeast from Carson City. Although this amount of uranium is small – about 5% of our current annual consumption – the discovery is of interest both for its scientific value and as an indication of the potential of the NURE program.

The measured uranium concentration in Walker Lake is 130 parts per billion (ppb), about 30 times higher than in seawater. Other bodies of water also contain uranium but generally in concentrations much lower than Walker Lake. Great Salt Lake has about 5 ppb, the Caspian Sea 3 to 10 ppb, and most lake and stream waters about 1 ppb. By comparison, however, the uranium ores currently being mined in the U.S. have concentrations in excess of 10 million ppb.

The NURE program, briefly described in the May 1975 *Energy and Technology Review*, involves four major ERDA laboratories. They are conducting systematic hydrogeochemical and stream-sediment surveys throughout the U.S. to locate uranium-rich areas. LLL is responsible for seven western states: Arizona, California, Idaho, Nevada, Oregon, Utah, and Washington. The University of Nevada's Desert Research Institute is assisting us. Sampling is continuing in central Nevada and will be expanded to other parts of that state and to other states later this year.

Although of scientific interest, the discovery's economic importance is yet to be determined. It is not known whether uranium extraction from Walker Lake is feasible. Ion-exchange recovery methods exist that are capable of extracting uranium from the oceans, but tidal action is harnessed to do the pumping. In lakes, some other pumping mechanism is required; the added expense might prohibit economical recovery.

HAWAII ENERGY PROFILE

LLL has recently completed a compendium of background information on the energy situation in Hawaii. This profile is part of our on-going efforts to help the State assess its technological needs, identify technologies developed here or at other national laboratories that are applicable to those needs, and identify areas where ERDA might initiate beneficial R&D programs.

Hawaii's energy requirements are currently being met by petroleum and manufactured gas. With no oil resources, Hawaii is entirely dependent upon imported, tanker-carried petroleum products and thus highly vulnerable to dislocations in the energy market from an embargo. It has no flexibility to shunt and shuffle a variety of energy supplies as can be done among mainland states.

Literature data show that the Hawaiian economy has a total energy inefficiency of 70%, much higher than the national average of 47%. This inefficiency results largely from the conversion of oil to electricity and the impact of an energy-intensive tourist industry. Also, some 59% of the petroleum is used for transportation, a fact that completely dominates the economy and reflects the State's geographical position as a crossroads for air and sea traffic.

The Hawaiian economy – and its energy supply and demand profile – is also dominated by one island: Oahu. With just 11% of the State's land area, Oahu accounts for 80% of Hawaii's economic base, 74% of its electric power generating capacity, 82% of its population, and 75% of all registered vehicles.

Projections by various State agencies indicate that in the near term (to 1985), increased supplies of oil will be needed to sustain the economy. For the mid-term (1985-2000), fuel costs will be high and new energy technologies will have to be developed to prevent a substantial deterioration in the standard of living. For the long-term (beyond 2000), development of an alternative fuel such as hydrogen – from biomass energy or the electrolysis of water – may be the most feasible route to energy self-sufficiency.

R&D activities currently being conducted in the State are directed toward achieving these goals. As part of these studies, the Laboratory is investigating the feasibility of developing wind power as an alternate energy resource on Oahu. This research was briefly described in the December 1975 *Energy and Technology Review*.

ENVIRONMENT, HEALTH AND SAFETY

CHARACTERIZING STACK EMISSIONS FROM COAL-FIRED POWER PLANTS

LLL is conducting a program to evaluate trace-element emissions from western U.S. coal-fired power plants. As a first step we have compared emissions from two plants using venturi wet scrubbers and electrostatic precipitators to control emissions. For each case we have calculated the potential deposition from inhaling the fly-ash particles. Our results show that electrostatic precipitators reduce the potential particle inhalation more than venturi scrubbers.

Burning coal at high temperatures makes smoke that contains significant quantities of toxic elements; inhaling these emissions is a potential danger to human health. Either electrostatic precipitation or wet scrubbing (see box on p. 2) can be used to control these emissions. In fact, the managements of many large western power plants are now considering installation of commercial wet scrubbers to comply with sulfur-oxide emission standards.

These wet scrubbers are highly efficient in removing particles larger than 1 μm (greatly reducing plume visibility). However, they are generally less efficient than electrostatic precipitators in removing submicrometre particles. Unfortunately, many of the more toxic inorganic elements in coal become concentrated on these smaller particles: the vaporized toxic elements condense on particle surfaces. Most stack emission particles deposited in the lungs are in this submicrometre range.

As a necessary step in understanding these potentially dangerous emissions, LLL has undertaken a study to characterize the trace elements emitted from coal-fired power plants that have been fitted with various control devices. We are currently taking measurements at two western U.S. mine-mouth power plants. Plant A, using tangentially fired burners and a cold-side electrostatic precipitator with a collection efficiency of 99.5 to 99.8%, burns 150 tonnes of pulverized subbituminous coal per hour. Plant B consists of five units that burn 950 tonnes of pulverized subbituminous coal per hour. Four of the five units at Plant B are being tested: two units with high-energy, variable-throat, wet venturi scrubbers and two units with cold-side electrostatic precipitators.

Both scrubber systems in the Plant B units use limed process water; each unit removes 99.2% of the incident particles and 30% of the sulfur dioxide. The units also use a front-fired burner and on each, during the two-week sampling period, the gross load varied from 215 to 242 MW.

Fig. 1. Setting up the sampling apparatus at a mid-stack port. The probe, with impactor stages and filter on the end, is about 5 m into the stack at the right. Emission gas that passes through the impactor stages and filter is pumped back through the black hose (left) and charcoal traps to a dry-gas meter. The stack's inside diameter is about 8 m.

Contact Richard C. Ragaini (Ext. 3512) for further information on this article.

Design efficiencies for the electrostatic precipitators on the two units in Plant B were 97% with all precipitator sections operational. (During our testing period, however, 4 of the 32 sections on one unit were inoperable, and the overall efficiency on that unit was estimated at 95%.) Both units used a front and rear burner design and during our testing period carried gross loads of 420 to 680 MW.

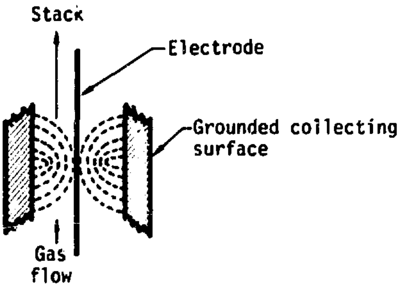
Samples were taken at mid-stack sampling ports such as that shown in Fig. 1. Particles were collected in-stack on filters and cascade impactors mounted at the end of the sampling probe. Emission gas passing through the impactor stages and filter was pumped back through charcoal traps to a dry-gas meter. This enabled us to normalize particle samples for a given emission gas volume. Samples of coal, precipitator hopper fly ash, bottom ash, and scrubber hopper slurry were taken at the same time. The results of the approximate analyses of the coal burned during the testing period are given in Table 1.

Particle-size distribution parameters for stack aerosols were obtained from scanning electron microscopy.[1] Figure 2 shows the size distributions observed for stack emissions from scrubber and precipitator units at both plants. Each curve has two obvious distribution peaks. The small-particle peaks include particles condensed from stack vapor; the large-particle peaks represent the distribution of fly-ash

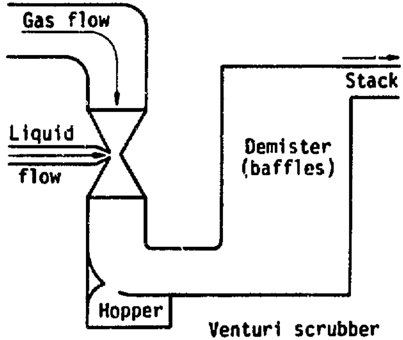
EMISSION-CONTROL DEVICES

Electrostatic precipitators are highly efficient particle collectors consisting of a negative discharge electrode and a grounded collecting surface. The emission gas passes through a high-voltage, direct-current corona established between the electrode and the grounded collecting surface. Suspended particles in the gas become highly charged and migrate to the grounded surface. Then the particles are dislodged by mechanical means, such as rapping or flushing with liquid, and fall into a removal hopper.

A hot-side precipitator works on emission gas that has been additionally heated after combustion. A cold-side electrostatic precipitator operates on emission gas just as it comes from the generator.



Electrostatic precipitator



Venturi scrubber

Wet scrubbers spray a liquid, usually water, into the emission gas. The liquid increases the size of the particles by colliding with them, facilitating collection; most of the larger particles are washed away. Such scrubbers are equipped with one or more of a variety of baffle plates or impingement stages that disrupt the straight-line flow of the gas.

In a venturi scrubber, the liquid is sprayed at right angles into the emission gas as it passes through a narrow orifice. The narrowness of the orifice causes an increased velocity and reduced pressure in the gas, both of which impart a greater efficiency to the scrubbing process. Often a lime slurry is sprayed with the water to reduce the sulfur-dioxide content of the flue gas.

Table 1. Analyses of coal burned during the testing period

Coal	Plant A	Plant B
Ash, %	23.2	9.2
Sulfur, %	0.52	0.46
Moisture, %	11.3	6.8
Energy content, MJ/kg (Btu/lb)	20.4 (8,760)	28.7 (12,330)

particles. The small-particle peak for the scrubber is at a conspicuously higher particle diameter than for the precipitators, probably because the particles are coated with water or process lime. The large-particle peak for the scrubber unit is narrower than the small-particle peak, demonstrating the scrubber's superior collection efficiency for large particles.

The curves in Fig. 2 apply only to relative numbers of particles; they do not reflect mass. Only 10% of the total mass of fly-ash emissions from the precipitator unit is in the form of small particles; 95% of the mass of fly-ash emissions from the scrubber unit is in small particles.

The small-particle peaks for Plant A and Plant B precipitator units agree, but the large-particle peaks show significant differences. Their operating efficiencies during the sampling periods were 99.7% (Plant A) and 95% (Plant B), the higher efficiency of Plant A resulting in the narrower large-particle distribution peak.

We analyzed all the samples for up to 27 elements by instrumental neutron-activation analysis of the seven individual cascade impactor stages and the backup filter used in each collection run. From these measurements we determined the particle-size distribution and mass median diameters for the individual elements and computed the emission rate and total mass for each element.

Table 2 lists ratios of element emission rates (for identical power generation rates) for the scrubber and precipitator units of Plant B. Emissions of small-particle species in Group I are 2 to 7 times higher from the scrubber than from the precipitator. Group II species are less volatile but are also associated with small particles. The emissions of the Group III species, which are least volatile and are associated with large particles, are greater for the precipitator than for the scrubber.

We used the pulmonary deposition function of the International Committee on Radiological Protection to calculate the total maximum particle deposition occurring in the lungs as a result of operating the precipitator and scrubber units tested.[2,3] Ratios of

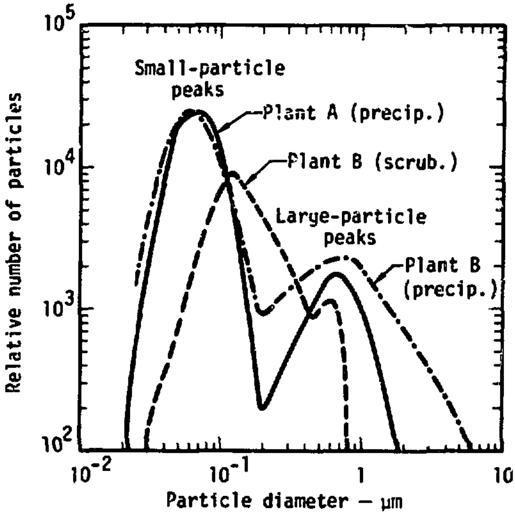


Fig. 2. Size distributions of fly-ash particles emitted from the stacks of two coal-fired power plants. Plant A uses a cold-side electrostatic-precipitator emission control system; Plant B has cold-side electrostatic-precipitator and wet-venturi-scrubber systems on separate units. The vertical axis plots relative numbers of particles, not mass, and the curves are not normalized and therefore cannot be compared as to total (mass) particle emissions.

scrubber-to-precipitator deposition are presented in the righthand column of Table 2. These ratios are conservative: some of the large particles emitted from the precipitator could fall out before the plume traveled far, reducing the precipitator inhalation hazard at a distance downwind and correspondingly increasing the deposition ratio.

For the small-particle species (Group I in Table 2), the pulmonary deposition for scrubber emissions ranges from 4 to 18 times greater than for precipitator emissions. For the large-particle species (Group III), relative potential lung deposition for precipitator emissions is about 3 to 7 times greater than for scrubber emissions. These elements, including cobalt, iron, aluminum, and scandium, are generally considered less toxic than those in Group I.

Table 2. Ratios of emission and potential pulmonary deposition rates for a wet venturi scrubber and an electrostatic precipitator

Element	Emission ratio[a] (scrub./precip.)	Deposition ratio (scrub./precip.)
Group I. Small-particle association		
Selenium	6.8 ± 0.5	17.9 ± 1.4
Barium	3.5 ± 0.3	8.9 ± 0.7
Antimony	2.6 ± 0.2	4.6 ± 0.5
Arsenic	2.4 ± 0.2	4.7 ± 0.3
Tungsten	2.0 ± 0.2	4.4 ± 0.3
Group II. Intermediate-particle association		
Uranium	1.3 ± 0.1	3.7 ± 0.3
Vanadium	1.2 ± 0.3	3.1 ± 0.9
Zinc	0.74 ± 0.14	2.2 ± 0.5
Calcium	0.7 ± 0.1	2.4 ± 0.4
Strontium	>0.4	>1.3
Mass	0.4 ± 0.1	1.3 ± 0.4
Group III. Large-particle association		
Cobalt	0.42 ± 0.03	1.3 ± 0.4
Gallium	0.29 ± 0.03	0.98 ± 0.16
Iron	0.21 ± 0.02	0.72 ± 0.09
Aluminum	0.17 ± 0.01	0.56 ± 0.10
Sodium	0.17 ± 0.01	0.55 ± 0.10
Thorium	0.096 ± 0.007	0.31 ± 0.12
Scandium	0.094 ± 0.007	0.30 ± 0.17
Lanthanum	0.093 ± 0.007	0.29 ± 0.11

[a] Uncertainties quoted are those of the elemental analyses only.

In the units tested, plume visibility was far less on the scrubber-equipped units than on those equipped with precipitators. However, the scrubber units, by concentrating trace elements on small particles, allow emissions with the greater potential of toxic element deposition in the lungs.

We are now entering the second phase of our program to evaluate trace-element emissions from western U.S. coal-fired power plants. Here we will examine the chemical speciation of the elements in the particulate emissions, important because an element's chemical form partially determines its toxicity in the lungs: certain chemical species are broken down by lung fluids more easily than others. We are also studying the surface structure of these particles. The position of an element in a particle — for example, at its core or on the outside surface — is important to its toxicity.

We are currently carrying out downwind plume sampling at Plant B in collaboration with the University of Maryland Atmospheric Chemistry Group and the National Center for Atmospheric Research. Particle and gas samples are being taken with aircraft-mounted cascade impactors and charcoal traps. These samples are then analyzed at LLL for trace-element content and sulfur speciation to determine any atmospheric physical and chemical transformations occurring among the fly-ash particles.

We are also evaluating the solubility in lung fluid and the biologic availability of potentially toxic elements in fly ash in collaboration with the Radiobiology Laboratory at the University of California, Davis. These data from the plume and availability experiments will then form the basis of a more sophisticated evaluation of the inhalation exposure to fly ash.

Key Words: coal — environmental studies; electrostatic precipitators; fly ash; power plants — environmental studies; scrubbers; trace element contamination; wet venturi scrubbers.

SAFETY AND SAFEGUARDS: DEFINING THE ISSUES

The Nuclear Regulatory Commission has the responsibility to ensure that commercial nuclear activities are carried out with adequate safety and safeguards. To meet this *responsibility, the* Commission is funding a number of research programs to develop the best safety and safeguards techniques; LLL is working on several of these. The purpose of this article is to define the issues involved in safety and safeguards.

Nuclear power's increasing role in meeting energy requirements has become a major focal point for public debate. Among the concerns expressed, two that are receiving increasing attention and study are safety and safeguards. The differences between these two concerns are fundamental, although, in some cases, the same technology or procedural changes can ameliorate both. Everyone involved in debating these issues agrees that high levels of safety and safeguards are an essential precondition for operations involving nuclear materials.

Safety and safeguards are most usefully distinguished in terms of the presence or absence of malevolent intent. Safety is concerned with accidents: situations that are not only unintended but, when they occur, surprise everyone. By contrast, safeguards focus on preventing purposeful, malevolent, or unauthorized actions: actions undertaken by someone with hostile intent. Of special concern here are any attempts to divert fissile materials that might be used to create a nuclear explosive or to divert radioactive material that might be scattered to create a contamination hazard. Certainly the apparent global increase in terrorism incidents has exacerbated such concerns.

One area – sabotage – *brings together both safety* and safeguards. Many of the design features incorporated to ensure safety will limit the nature and extent of what sabotage can achieve. However, sabotage is more customarily and adequately addressed under safeguards, in that the malicious mind can *conceive of event sequences that are most unlikely to* occur by chance or inadvertence.

In simplified terms, then, it is sometimes said that safety deals with acts of God while safeguards deal with acts of men. Nevertheless, both potential hazards result from man's activities and their prevention *requires adequate forethought* and regulation.

The Nuclear Regulatory Commission, established as a separate federal entity in January 1975, has the responsibility for establishing the regulations governing commercial nuclear activities in the United States. *Thus it has the statutory responsibility* of ensuring that such nuclear activities are carried out with adequate safety and safeguards. Not only must it establish adequate regulations, but it is also required to carry out inspections to ensure compliance.

Furthermore, there is an opportunity for U.S. *leadership internationally* insofar as good practices established within the U.S. are adopted by the International Atomic Energy Agency or are enforced as preconditions on export sales. Such action internationally is an outgrowth of this nation's Atoms for Peace program. Only if adequate safeguard measures are developed and applied can the goals of this program be achieved without contributing to a worldwide proliferation of nuclear weaponry.

In pursuit of the innovations required to execute *its responsibilities, the Commission is funding* a number of research programs at LLL. ERDA, with its continuing responsibilities to develop new energy technology, shares many of these safety and safeguards interests. If nuclear power is to provide a substantial fraction of the global energy needs of the future – and these needs could be very large indeed if the less-privileged peoples are to markedly improve their position – then success in these programs is essential. Suitable safety and safeguarding techniques must be devised to cover all of the steps in the nuclear fuel cycle: production, enrichment, fuel element fabrication, transportation, power reactor use, spent fuel reprocessing, storage, and waste disposal.

In the course of our work for ERDA, we have developed expertise that is applicable to many nuclear safety and safeguards issues. For example, our experience in the area of seismic effects is now being applied to a study of the effects of earth shocks on nuclear power reactors. Our initial concern *in this area* was related to underground weapons' tests, and this remains of interest today. However, much broader studies of earth/explosive interactions were required for the Plowshare program's investigation into peaceful uses of nuclear explosives.

More recently, with the advent of treaties limiting test yields, the need for monitoring techniques based on seismic measurements led us to analyze the frequency and detailed structure of seismic events. In now applying the understanding garnered from these

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Contact Marvin R. Gustavson (Ext. 7436) for further information on this article.

activities to the issue of reactor safety, we are also drawing on such LLL capabilities as computer codes that describe wave amplification, resonances, and fracture.

This seismic effects study illustrates two basic aspects of safety research. One is the need to include in any analysis the strains or extreme conditions that may be imposed by the environment. The other is the need to understand how the system as a whole will react to perturbations or even failures in one or more of its parts. Of course, the human operators themselves can be a source of these failures, or their actions in an emergency may be less than optimum. Thus the human factor is never far from consideration in safety analysis, although one always strives to achieve "accident-proof" or "fail-safe" designs.

In the safeguards area, the human element is not simply part of the problem, it is the problem's source. Since safeguards deal with preventing intentional acts, specifying the threat posed is a central issue. This, too, is not a new problem for LLL, although its early form was in a different guise – namely, devising the technology and procedures to ensure that nuclear weapons would only be used by decision of the National Command Authority. Threat specification was a key element in that work, with primary importance being assigned to the knowledge, equipment, and goals of the hostile group and to the timespan of its efforts.

In terms of the nuclear fuel cycle, another key issue is what magnitude of diversion – how much fissile material – is of consequence? Specifically, how much does it take to make a bomb? ERDA, with its responsibilities to develop nuclear weapons, is the senior national advisor on this subject, and LLL's specialists are required to provide a basis of expert opinion. This question is more complex than it appears. A terrorist group might, for example, be satisfied with building an inefficient device that has only one chance in ten or a hundred of achieving even a low yield.

A complicating aspect of this issue is that the diversion need not occur all at once but may occur piecemeal over very long periods. Devising the technology and means to preclude such an occurrence *while not unduly inhibiting fuel-handling operations* is the primary goal of LLL's program on material-control systems. This program, described in the following article, involves the development of methods to evaluate nuclear material-control systems and strategies and the conceptual design of exemplary systems. The greatest opportunity for diversion may occur in processing nuclear materials. Hence, an ability to understand such processing operations in detail, to devise appropriate process control instrumentation and quantify its performance, and to design automated monitoring systems that would give positive warning of any deviations from authorized procedures is important in carrying forward this work. Automation and cross checking are critical since we must assume that the diversion team could involve employees within the complex. In fact, many analyses assume that blackmail to attain such cooperation constitutes a likely *modus operandi* for some threat groups.

The diversion of fissile material for use in fabricating a nuclear explosive is not the only eventuality that must be guarded against. Lesser amounts of fissile materials such as plutonium or radioactive wastes might be removed and scattered to create a contamination hazard. Or no diversion at all may actually occur and yet a threat may be made; that is, a hoax attempted. Here again, being able to account for all materials on a real-time basis may be critical in selecting the proper response.

The safety and safeguards studies reviewed in the following article and in future *Energy and Technology Review* issues are a part of the story of man's efforts to cope with his own growing technical abilities. Indeed, nuclear technology is seen by some as having become an important public issue largely because it serves as a lightning rod for more general concerns about technology, the changes it gives rise to, and the nature of our future. In that sense, these studies are at the leading edge of man's efforts to be the master of his own fate.

Key Words: nuclear materials; nuclear materials management; nuclear safety; safeguarding nuclear materials

CONTROL OF NUCLEAR MATERIALS: SYSTEM EVALUATION AND DESIGN

The Laboratory is conducting a safeguards program for the Nuclear Regulatory Commission to develop methods for assessing the control of nuclear materials at licensed nuclear facilities. The program has two objectives: develop evaluation methods and tools for both existing and proposed material-control systems, and design exemplary material-control systems. We are presently developing a hierarchy of mathematical models to relate control strategies at fuel reprocessing plants to their counterdiversion objectives.

The diversion of nuclear materials constitutes a potential threat to public health and safety through two possibilities: fissile material can be fabricated into nuclear explosives or released to create a radiological hazard. To minimize this threat, the Nuclear Regulatory Commission requires that safeguards be implemented at all licensed nuclear facilities to prevent diversion. A material-control system is part of these safeguards. As the Commission's prime contractor in material-control research, we are conducting a program directed toward improving control strategies at nuclear processing facilities.

Material-control systems must perform three counterdiversion functions: (1) limit diversion opportunities, (2) detect diversions or diversion attempts, and (3) respond to these diversions or attempts. The first objective of our safeguards program is to develop analytical techniques for evaluating how well existing and proposed material-control systems can and do perform these three functions. A second objective is to design exemplary control systems. Our initial focus is on control systems for the tail end of the light-water reactor fuel cycle – specifically, irradiated fuel reprocessing and mixed-oxide fuel fabrication. Additional facilities to be considered later include other reprocessing and fabrication plants and high-level-waste treatment facilities.

Diversion at fuel reprocessing plants is defined as any unauthorized removal of nuclear material from either the processing flow streams or interim storage locations along these streams. The prime concern is covert theft by an insider, although other possibilities – such as overt theft and sabotage – must also be considered.

Program Approach

Our approach to evaluating the performance of material-control systems is to develop a hierarchy of mathematical models relating the various control strategies and procedures to their counterdiversion objectives. This mathematical framework is based on utility theory, which allows us to quantify the relative importance of various control system factors and ultimately to compare control systems to one another or to a predetermined standard.

There are four basic considerations in evaluating a material-control system:

- How well does the system perform its intended duties?
- How will the system affect plant operations?
- What does the system cost?
- What impact will the system have on society?

Utility theory gives us a basis for assigning a "worth" or numerical value to each of these considerations and then combining these values to arrive at a single "worth" for the total material-control system. Our present work focuses on developing the mathematical models needed to assess system effectiveness.

In constructing these models, we are following a "top down" approach that will take us from our basic analytical tool – a utility model – through a hierarchy of successive mathematical models and down to the specific characteristics and procedures of a plant's processing flow streams and material-control system. We begin by identifying the variables or attributes needed to evaluate system effectiveness. Goals and consequences are our first concern. By goal we mean the objective of an adversary within a reprocessing plant. It might be to steal 20 kg of plutonium or to sabotage a certain part of the plant. Consequence is the potential danger to society if the adversary succeeds; for example, it might be the death of 20 000 people.

We must then ask what is the probability of a diversion attempt being made to achieve a given goal, and if made, what will be its outcome? Examination of the probabilities of all possible diversion attempts and of all possible outcomes should allow us to assess the control system's capability. However, to estimate these probabilities, we need to break them down further. We must evaluate the adversary and his view of the reprocessing plant, and we must estimate the plant's ability to counter an adversary's actions.

Contact Lynn L. Cleland (Ext. 8053) for further information on this article.

To estimate the probability of a particular diversion attempt, we need to identify the parameters that determine theft attractiveness and the deterrence provided by a plant's material-control system, both of which influence an adversary's target choice. These parameters will include how the adversary assesses his probability of success, the value (monetary, political, etc.) of the goal to him, and the potential risk to his health or life resulting from a diversion attempt. To determine how an adversary perceives his chances for success, we must also develop an adversary model.

To estimate the probability of a specific outcome to a diversion attempt, we must analyze how the material-control system will respond. For this analysis, we must further reduce the problem to how individual components in the system will function. These components can be categorized as either active or passive.

Under active, we have monitoring and reaction components. The former monitor conditions in the plant and supply information to the decision and logic parts of the control system. In the event of a diversion attempt, reaction components notify the safeguards system and create commands for safeguard devices. They may also alter materials or processes to reduce the probability of a successful diversion.

There are likewise two basic passive components. The first of these, stimuli-enhancement components, create more easily detected stimuli for the active components. A stimulus is defined here as a sequence of signals resulting from an adversary's actions. For example, an attempted intrusion of a glove box may be easier to detect if the box is pressurized. The second, opportunity-reduction components, force the adversary to take more obvious actions. Strategically located physical barriers would fall into this category.

Figure 3 represents a *material-control system.* The existence of all components within this system influences an adversary's perception of his success probability, thereby changing the probability of an attempted diversion. The performance of these components will determine material-control system response.

The performance of an active component will depend on the stimuli generated from an attempted diversion. It is therefore necessary to know the probability of stimuli. Because these stimuli will result from the adversary's physical actions during an attempt, we must determine them, in turn, from the time sequence of actions associated with that attempt. This determination is the last step in our "top down" decomposition; it completes the derivation of our mathematical framework. Figure 4 depicts the evaluation process that results from that framework.

Our present efforts are thus directed toward developing a mathematical framework that rests on variables describing the material-control system and components, the reprocessing plant, and the adversary.

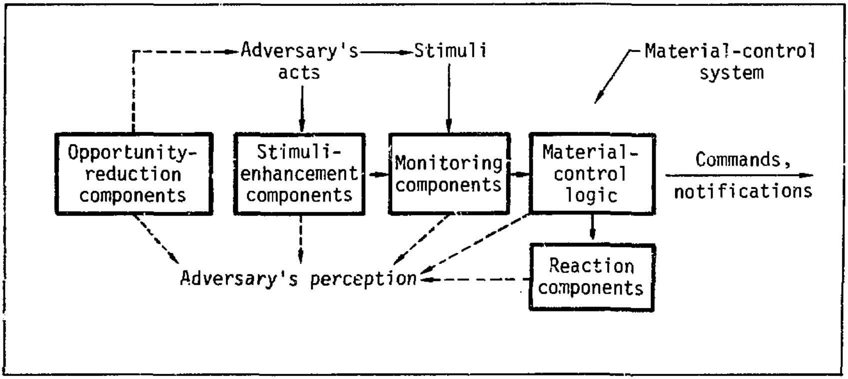

Fig. 3. Representation of a material-control system. Opportunity-reduction components force the adversary to select paths for which diversion is more easily detected. Stimuli-enhancement components create more easily detected stimuli. These stimuli are then operated on by monitor components to create the signals that are the basis for decisions made by the material-control logic. On command from this logic, reaction components serve to reduce the probability of a successful diversion.

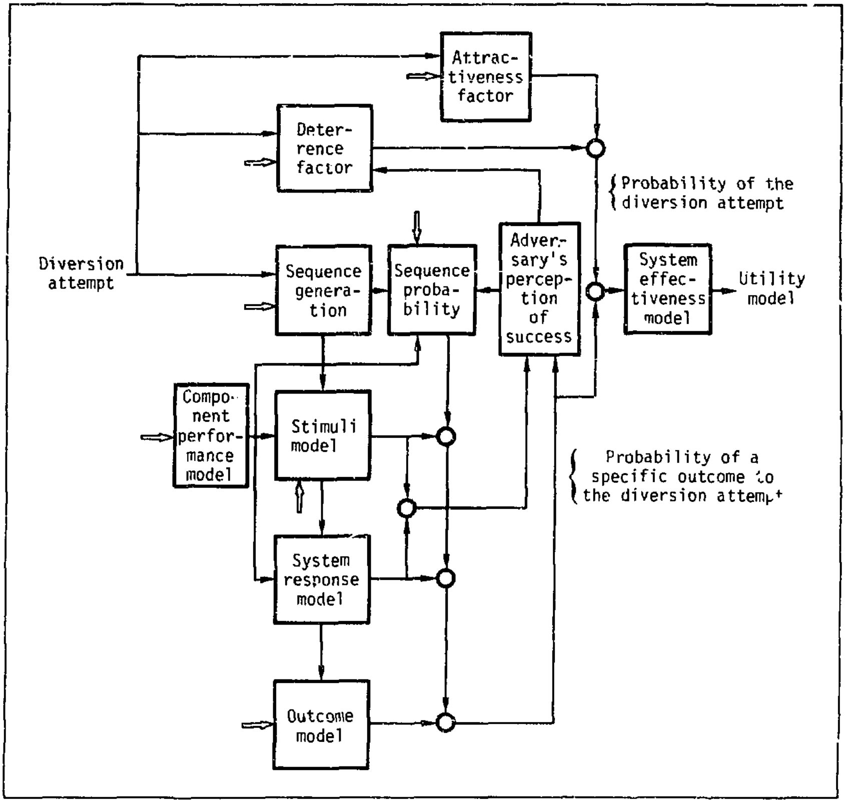

Fig. 4. Evaluation process for determining the effectiveness of a material-control system. Circles represent algebraic computations. The open arrows indicate where facility, process, and material-control system data are required.

The computer models developed through this effort will support the Nuclear Regulatory Commission in its choice of effective regulations by assessing the effects of changing material-control strategies. When a complete utility-model hierarchy is validated, it will be used for assessing licensee proposals. It may also be used to establish general regulation criteria.

We will use the model hierarchy to fulfill the second objective of our safeguards program: designing exemplary material-control systems. The hierarchy will allow us to determine specifications for material-control systems and components. Tradeoff analyses will be performed by exercising the utility model and its constituent models, thereby identifying preferred material-control system configurations.

Program Development

To achieve our two objectives, the program has been divided into three development areas: systems engineering, material-control component design, and facility characterization. The three areas are interactive and are being pursued concurrently.

The systems engineering group is responsible for developing the evaluative tools and conceptual designs for material-control systems. Our principal concern here is the total system – developing appropriate assessment methods and designing effective exemplary systems.

The group for material-control component design is evaluating the design and performance of specific functional components for material isolation, material handling, measurements and instrumentation, and data processing and analysis. This development work centers on the individual components and processes that make up a control system.

Finally, the facility characterization group is providing the process and security information needed to design and evaluate control systems and components. Here we are examining the physical layout of existing reprocessing plants and the various chemical and mechanical processes involved in their operation.

Key Words: material control systems; nuclear materials; nuclear materials management; safeguarding nuclear materials.

SCIENCE AND TECHNOLOGY

TAKING FAST-NEUTRON SNAPSHOTS OF THERMONUCLEAR PLASMAS

Attempts to study thermonuclear plasmas have long been hampered by our inability to image their neutron-producing regions. X-ray pinhole cameras are ineffective for this purpose; their walls and pinhole aperture plates are too transparent, their films too insensitive. We have constructed a special pinhole camera that solves these problems, imaging a 1-cm^3 volume that emits about 10^{12} neutrons in 10 to 100 ns with a resolution of 1 mm and a "shutter speed" of about 10 ns. With this camera we have investigated dense plasma-pinch phenomena and plan to diagnose a variety of inertially and magnetically confined thermonuclear plasmas.

Fast neutrons are one of the main products of a thermonuclear reaction experiment, and measurements of the number and energy spectrum of these neutrons are among the primary diagnostic means for investigating plasma dynamics. This information is incomplete, however, in that it gives no hint of the size and location of the neutron-emitting region. Without a neutron-imaging system, plasma physicists are in somewhat the same position as a blind man who feels the warmth of the sun but has no idea of its size and shape.

We have developed a fast-neutron pinhole camera with high detection efficiency and nanosecond time resolution. It combines a specially designed copper collimator with a variety of interchangeable neutron detectors at the image plane. Resolution is adequate to show the size and shape of the neutron-emitting region in the plasma.

Pinhole cameras are nothing new, of course. They predate photography, having been used by Renaissance artists in their studies of perspective drawing. X-ray pinhole cameras have been used for plasma diagnostics for many years.

Adapting this well-known principle to neutron imaging involved a number of ingenious innovations, however. For an optical pinhole camera, the walls and pinhole aperture plate can be thin sheet metal or even cardboard. For an x-ray pinhole camera, they must be a few millimetres of lead. For our neutron pinhole camera, the walls became a pair of 1-m-thick water-and-concrete shields (Fig. 5), and the pinhole

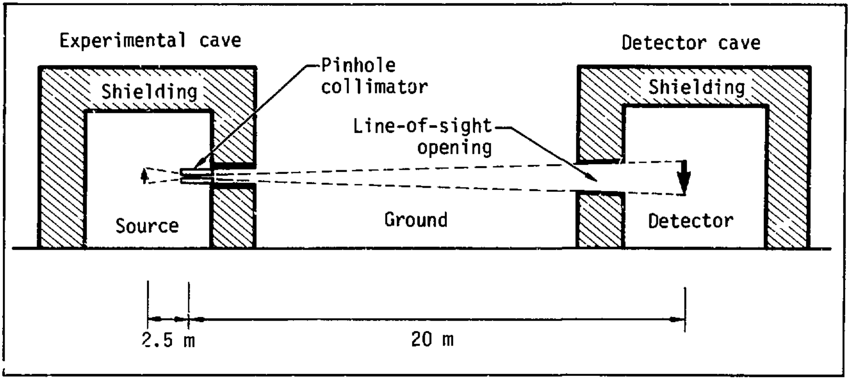

Fig. 5. Schematic diagram of the shielding and collimation setup for the neutron pinhole camera experiment. An object distance of 2.5 m, together with an image distance of 20 m, gives an image magnification of 8. The overall flight path of 22.5 m allows clean time-of-flight separation of the neutron pulse from the prompt gamma-ray signal for typical pulse widths of 100 ns or less.

Contact Rudolf W. Bauer (Ext. 7527) for further information on this article.

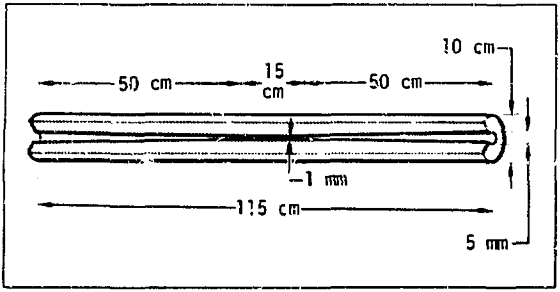

Fig. 6. Geometry of the neutron pinhole collimator. This collimator was originally machined from copper. Later versions cast in copper-loaded epoxy proved entirely satisfactory.

became a 115-cm-long copper collimator with a 1-mm central aperture 15 cm long (Fig. 6).

Making such a collimator of solid copper is no easy task. Imagine boring a 1-mm hole 15 cm long in the middle of a copper bar, and boring two more holes, aligned with the first, that taper from 1 mm to 5 mm over a length of 50 cm. Such impossible specifications could be met only by subterfuge: first we milled two copper bars lengthwise and keyed them to fit together perfectly; then we milled grooves of appropriate dimensions in the mating faces so that when reassembled, the composite bar would have the required central hole.

After making a couple of these solid copper collimators, we thought of an easier, faster, and less expensive method. We made a mandrel the shape of the desired holes, inserted it into a simple mold, and filled the mold with copper-loaded epoxy plastic. Removing the mandrel left the finished piece with the required central hole. The high concentration of copper in the epoxy (80%) enabled this inexpensive collimator to perform almost exactly like the solid-copper original.

As shown in Fig. 7, we installed these collimators in pairs aimed at the same source point. This offers the possibility of making stereoscopic views, and also provides a convenient way of comparing competing imaging systems.

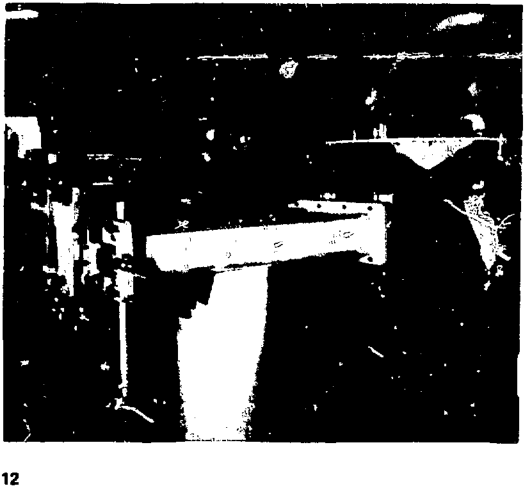

Fig. 7. A pair of copper collimators installed in the neutron-pinhole-experiment cave. The collimators define two lines of sight diverging from a common source point (object center) to the left in the center of the shielding enclosure. Each collimator serves a different detector station 20 m away to the right in the detector cave.

Image Recording

X-ray pinhole cameras commonly use photographic film for image recording. To record neutrons efficiently, however, we would need a stack of emulsions some 5 to 10 cm thick. It would then take many months to process the film, and the reconstituted image would be integrated over the entire neutron pulse (100 ns). There would be no practical way to resolve events 10 ns apart, as was desired. Such resolution requires some form of electronic detection.

For use with this fast-neutron pinhole camera we have devised three different neutron imaging systems. Each has advantages and drawbacks, each represents a compromise with the ideal. Together they constitute a system that offers 1-mm spatial resolution and 10-ns time resolution and that provides a first look at the neutron image within about 15 minutes of the neutron pulse.

The first, and in some ways the most direct, detection system consists of a hexagonal array of 61 small plastic scintillators, each connected by a shielded light pipe to a separate photomultiplier tube (Fig. 8). Each scintillator is a cylinder 1 cm in diameter and 5 cm long, shielded from adjacent scintillators with 25-μm-thick aluminum foil.

These dimensions were chosen to minimize cross talk between the different image elements; only about half of the neutrons entering the front face of the array will interact (and cause a scintillation) before travelling through the array, and very few of those that interact once will do it again in a different scintillator before they also escape. Similarly, no more than about 1% of the neutrons will bounce back from the plastic light pipes and make a scintillation in any part of the array. As a result, we can be sure that at least 95% of all the scintillations in a given scintillator represent neutrons that came directly from the plasma source, through the collimator, and to that image element, i.e., that are bona fide members of the neutron image.

The output of each of the photomultiplier tubes is separately amplified and displayed, together with timing fiducial markers, on several oscilloscopes. These oscilloscope traces represent not the individual light flashes from each neutron interaction, but the total light output of the scintillator as a function of time. The various oscilloscopes have different sensitivities; the more sensitive ones record the beginning of the light pulse, and the less sensitive ones display details near the peak of the light emission. These scores of traces can then be digitized, divided into 10-ns slices, and combined into a series of images that show how the neutron-emitting region builds up and decays.

This 61-element array represents a tradeoff in favor of time resolution. The image may be somewhat crude, but the time resolution is excellent. The two other detectors sacrifice time resolution in favor of improved image quality.

The scintillation-fiber system (Fig. 9) is similar in principle to the scintillation-photomultiplier system described above. Instead of 61 image elements, however, it crowds about 1000 plastic scintillating fibers, each 5 cm long, into a 9-cm bundle. This gives it greatly improved spatial resolution. We connect all 1000 scintillating fibers directly to the faceplate of an

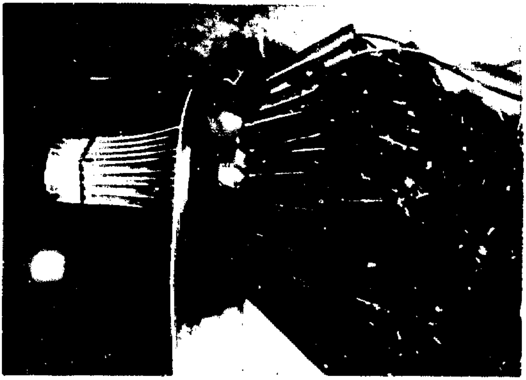

Fig. 8. Assembled 61-element scintillation-photomultiplier system used in the neutron pinhole camera as an imaging detector with an inherent time resolution of a few nanoseconds. The neutron flux comes in from the left. Curved aluminum-wrapped light pipes connect each individual scintillator to a corresponding photomultiplier tube.

image-intensifier tube that amplifies the light output about 10^5 times, making it possible to photograph the resulting image on 70-mm film.

The image-intensifier tube can be switched on and off in 50 ns, enabling us to image either the beginning, the end, or the middle of a 100-ns light pulse. There is no simple way with this equipment to image an adjacent 50-ns slice of the same light pulse, however. By the time the 70-mm camera presents the next frame of film, the original light pulse is long gone. It takes an entire separate scintillator-intensifier-pinhole system and meticulous cross timing to obtain an image of an adjacent 50-ns slice of the same light pulse.

The picture recorded on the 70-mm film is a featureless blob with indistinct boundaries that blend imperceptibly into the background. Scanning this photograph with a microdensitometer produces a contour map of the film density that is much simpler to interpret. Figure 10 (upper pair) shows such a map, together with a 61-element view of the same deuterium-tritium plasma pulse taken through an adjacent collimator. The two views agree well on the size and shape of the neutron-emitting region, and on its displacement from the optical center.

The lower pair of images in Fig. 10 shows a change in the location of the neutron-emitting region. This displacement supplies important operating information. It enables us to apply corrections to center and focus the plasma for more efficient operation of the plasma machine.

The third neutron imaging detector is a modified propane bubble chamber (Fig. 11). In conventional bubble chamber applications, we wish to examine individual particle tracks and observe how they curve in a magnetic field or how they branch. To best show these features, we place the camera at right angles to the beam direction. In neutron imaging, however, we only wish to record where each neutron interaction took place; for this we align the viewing window and the camera with the beam axis, i.e., with the collimating pinhole.

In this detector, the neutron interactions of interest take place in a cylindrical volume 10 cm deep and 10 cm in diameter in superheated liquid propane. Each neutron interaction leaves behind a trail of ions on which bubbles can form if the pressure on the bubble chamber is released just after the neutron pulse. Each of these bubbles serves as a scattering center for the side light. This scattered light stands out brilliantly against the all-black background and can be photographed with a conventional camera set to the smallest aperture for the maximum depth of field.

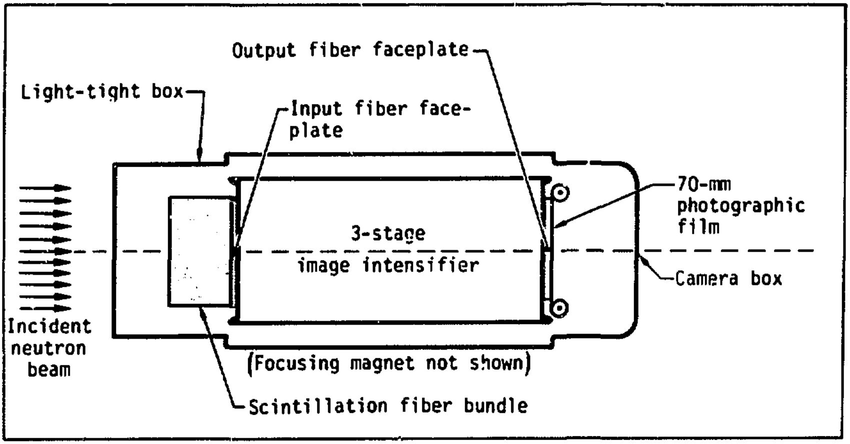

Fig. 9. The scintillation-fiber-chamber image-intensifier system used as an imaging detector for the neutron pinhole camera. The scintillator fiber bundle, about 9 cm in diameter and 5 cm thick, consists of some 1000 individual plastic scintillator rods 3.2 mm in diameter. Quartz-fiber faceplates couple the scintillator bundle to the first cathode of the image intensifier and the output screen to the 70-mm photographic film.

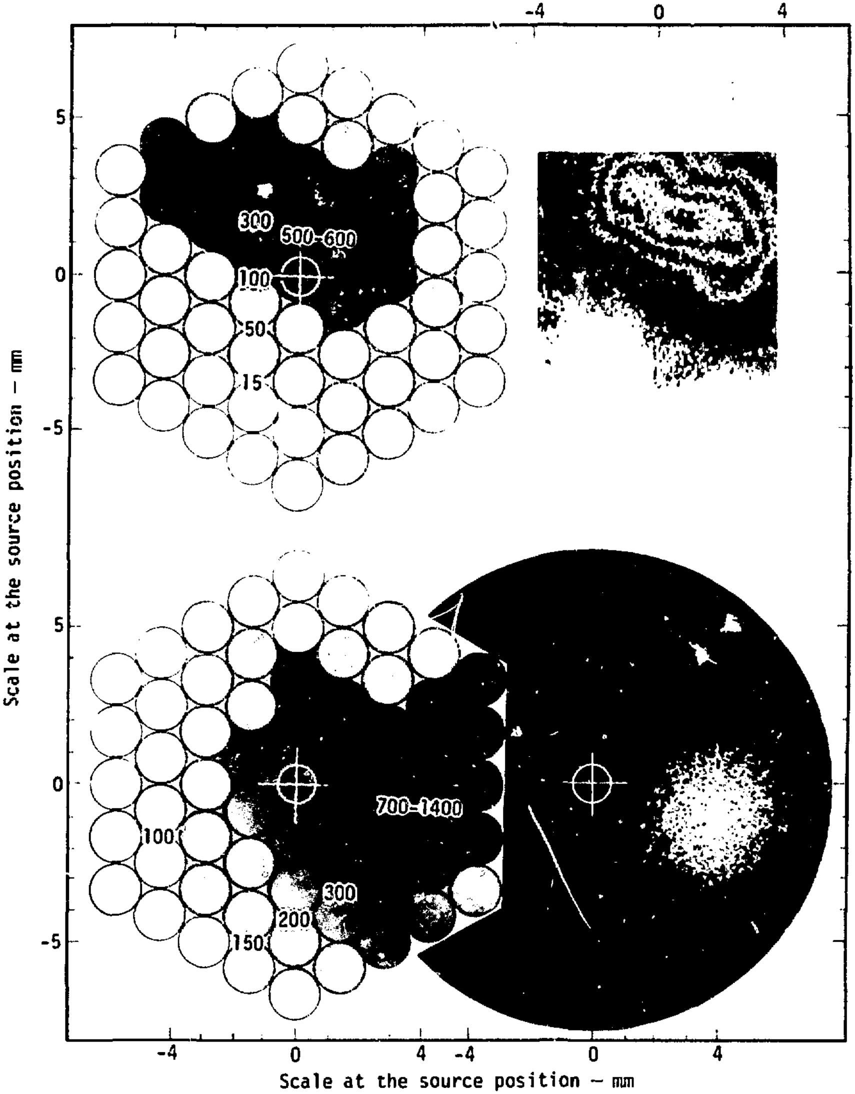

Fig. 10. Neutron-imaging detector comparisons. Upper pair: a 61-element scintillation-photomultiplier image (left) vs a 1000-element scintillation-image-intensifier image (right) of a D-T plasma pinch. Lower pair: a 61-element scintillation-photomultiplier image (left) vs a propane-bubble-chamber photograph (right) of a D-D plasma pinch. The 61-element images were drawn from the integrated light pulse data. The 1000-element image is an isodensitometer scan of the original photograph. The propane-bubble-chamber photograph is unretouched. Numbers in the 61-element arrays indicate the incident neutron flux (n/cm^2).

The lower pair of images in Fig. 10 compares a bubble-chamber photograph of a deuterium plasma with a 61-element image taken through an adjacent collimator. In both images the neutron-emitting region has moved closer to the horizontal axis, but is still far to the right. The agreement between the two views is evident.

The bubble chamber offers no time resolution at all within the neutron pulse, although it does discriminate against random background events more than a few hundred microseconds before or after the pulse. *It is even possible to distinguish between D-D and D-T neutrons at low flux levels.*

Summary

We have developed a pinhole camera for imaging sources of D-D and D-T neutrons with a resolution of 1 mm at the source. We have used this camera in several plasma experiments and demonstrated its ability to image 1-cm-diam sources emitting about 10^{12} neutrons.

We have devised three different image-recording systems and developed each to the point that they yield quantitative flux measurements. With a *61-element-matrix scintillation-detection assembly*, we have achieved a time resolution of about 10 ns and moderate spatial resolution. The limit on time resolution was imposed primarily by our oscilloscope recording system; wide-band oscilloscopes would permit a resolution of 2 to 3 ns. Our scintillation-fiber-chamber image-intensifier system has a time resolution of a few tens of nanoseconds and

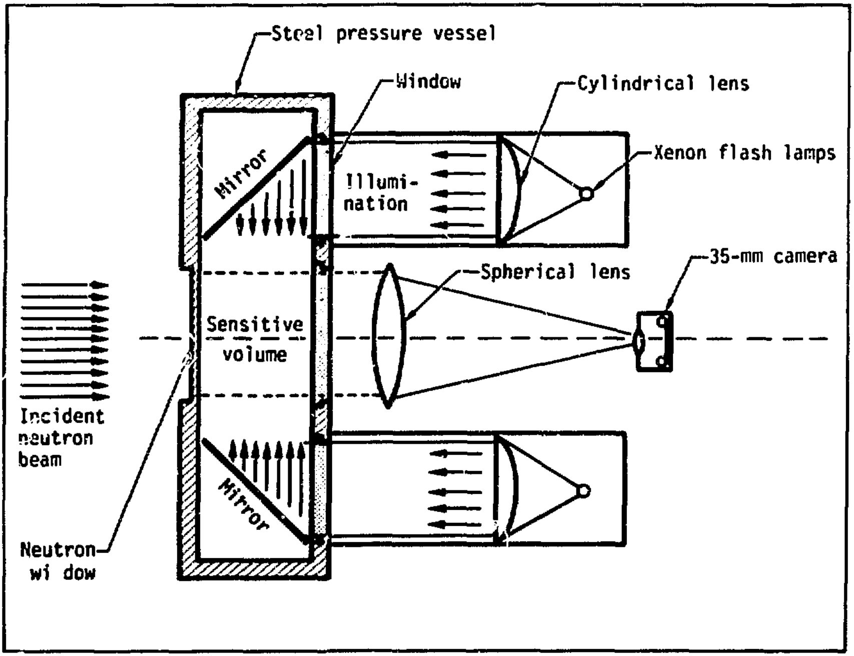

Fig. 11. Optical arrangements for the propane bubble chamber used as an imaging detector in the neutron pinhole camera. Photographing the neutron collision events throughout the sensitive volume (10 cm in diameter and 10 cm deep) requires an extreme depth of field. We achieved this by interposing a condensing lens and by stopping the camera down to the smallest aperture. The chamber operates at 2.5 MPa and 60°C.

good spatial resolution. The propane bubble chamber has relatively poor time resolution (milliseconds) but good spatial resolution.

The spatial resolution of all three systems is ultimately limited by our pinhole geometry; for the 61-element system, it is also limited by the relatively low number of image elements. All three detectors are about equally sensitive, with a lower response limit of a few neutrons/cm^2. They also permit fast information retrieval; 15 minutes between exposure and the first look at raw data is normal.

We carefully designed the pinhole geometry, using a Monte Carlo neutron transport code, to minimize scattering and to give about 1-mm spatial resolution. We found that an eightfold image magnification was a good compromise that took into account detector dimensions, time-of-flight separation between neutrons and gammas, and Doppler broadening of the neutron signal.

The neutron camera described in this article was a reliable and versatile tool in our investigations of dense plasma compression phenomena. We are planning to adapt it now to magnetic fusion and laser fusion experiments. These adaptations will be mainly a matter of scale.

Key Words: bubble chambers; deuterium – nuclear reactions; deuterium plasmas; plasmas; scintillators; scintillation detectors; thermonuclear reactions.

Notes and References

1. For a detailed account of our sampling techniques, measurements, and calculations, see R. Ragaini and J. Ondov, *Trace-Element Emissions from Western U.S. Coal-Fired Power Plants*, Lawrence Livermore Laboratory, Rept. UCRL-77669 Rev. 1 (1976), to be published in the Proceedings of the 1976 International Conference on Modern Trends in Activation Analysis, September 13-17, Munich, Germany.
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