thermonuclear fusion. (Use of electron beams in place of lasers may also be feasible. This is being studied mainly at Sandia Laboratories in New Mexico.)

Experiments conducted in the past 2 years at Livermore and the Los Alamos Scientific Laboratory, among other places, have produced miniature fireballs. But their output of x-rays and neutrons suggests that the thermonuclear "burn" has thus far been more of a smolder.

"What we're seeing is like touching a match to damp wood," one scientist said in an interview last year. "We see smoke but not fire."

The Hafstad panel said no physical problems had been identified that would prevent these experiments from leading to practical power production. But such a system, in the panel's view, would require each target pellet to emit 75 times more energy than the megajoule of laser light that goes into it. Even then, up to 45 explosions each second would be needed to generate power on a commercial scale. In contrast, a practical weapons simulation system would require a much smaller gain and a repetition rate of perhaps only three or four shots a day. Ports mounted in the walls of the target chamber would let radiation impact on hardware being tested.

To appreciate the weapons establishment's enthusiasm for such a device requires some understanding of the special difficulties of a business that, when stripped of its complicated ethical considerations, is revealed at heart to be a most arcane and expensive branch of physics.

It involves, weapons physicists point out, experimentation with materials at extreme physical conditions currently found only in the centers of stars and in bomb explosions. Moreover, carrying out physics and engineering experiments deep inside a mountain or thousands of feet underground in mined-out chambers of rock, as is the case at the Nevada Test Site, is ponderously slow and exorbitantly expensive. Since the Limited Test Ban Treaty was signed in 1963, prohibiting tests everywhere but underground, the United States has spent roughly $175 million annually to conduct 10 to 20 explosions a year at Nevada. In the fiscal year beginning this July the testing budget will go up to $210 million as the laboratories race to beat the March 1976 cutoff date for tests larger than 150 kilotons proposed last year as part of the Threshold Test Ban Treaty.

"People think we like to go out in the desert and shoot off bombs, but that isn't true," says one nuclear effects expert who has spent many years doing precisely that. "A test can take a year or more from conception to detonation, and they're usually oversubscribed with experiments. It's hot, you get sand in your relays, and things don't always go as planned. Believe me, it's no picnic."

A physicist whose involvement has centered on weapons design, not effects, emphasizes the difficulty of gathering data under these conditions: "Nothing survives in the thermonuclear environ-

Laser Fusion Report Plays Down Power Potential, Plays

The early hopes that laser techniques could provide a shortcut to fusion power have faded, and noted scientists have said that the government's laser fusion program is being oversold as an energy project. But the official Washington attitude remains sanguine. The first high-level review of the laser fusion program, released by the Energy Research and Development Administration (ERDA) in mid-March, recommended that it receive broader support, especially for research in universities and private companies. But the report made the point quite clearly that of all the possible applications of laser fusion (see accompanying story), commercial production of electricity was the most dubious.

The usefulness of laser fusion for electricity production depends on achieving what is called a high pellet gain, that is, a high return on the laser energy deposited in a fuel pellet from the fusion microexplosion that results. Using reasonably optimistic estimates of the efficiencies that might be expected from the various components of a laser fusion power station, the report found that a gain of at least 75-fold would be required for a practical power plant. The evaluation of the technical status of laser fusion concluded that "A pellet gain of 75 . . . may not be attainable under practical conditions. But the possibility is important enough to warrant aggressive development. Some significant pellet gain appears to be almost certain to be achievable. A failure to reach a gain of 75-fold will still leave other interesting possible applications of laser fusion. . . ."

The major application other than commercial power generation identified in the report is the simulation of nuclear weapons explosions. "The requirements of pellet gain are much less for this application than for commercial power production," the report said. Another possible use, being pushed more strongly by the advocates of laser fusion now that the future of the breeder reactor program looks cloudy, is the generation of fissile fuel from the neutrons produced through laser fusion. This might be done in a hybrid fusion-fission plant. Other schemes would separate laser fusion plants breeding plutonium from the light-water reactors burning plutonium to produce commercial power as well as power to run the laser plant. Most laser fusion researchers say that only a gain of 1 would be needed for the laser breeding schemes to work. The maximum gain achieved in actual experiments, which might be more accurately called a minimum loss, is about 10^{-7} (*Science*, 27 December 1974).

A major unknown factor that will determine how much laser power is needed to reach a certain energy gain is the degree of fuel pellet compression. The report found that 10,000-fold compression of solid hydrogen was probably an upper limit, and that a lesser compression of 1000-fold would require an extremely powerful laser. In between these two values, a compression of 5000 was judged to be the minimum necessary for a practical power plant.

Even at this high degree of compression, a 1000-

ment. You do an experiment once and it's done. If the results were not as you expected it is very difficult to repeat.

"With laser fusion we are getting close to thermonuclear reactions, explosions, for the first time. In the laboratory you can just repeat your experiments at will."

Concern about the effects of nuclear weapons—the vulnerability of military hardware—has centered over the years in the Pentagon's Defense Nuclear Agency, while the task of weapons design and testing was the AEC's responsibility (and now is ERDA's).

Over the years the DNA, in seeking to reduce its reliance on underground explosions, has developed an extraordinary array of machines and techniques for simulating portions of the weapons radiation spectrum, which runs from radio frequencies up to gamma rays of about 14 million electron volts. DNA officials express cautious optimism that laser fusion will represent an important evolutionary advance over existing machines.

One area of prime interest concerns the effects of x-rays and gamma rays on electronics systems in, for instance, missile warheads or communication satellites. To reproduce the physical shock and electric discharge effects of this radiation, the Defense Department has built some 35 huge flash x-ray machines in laboratories across the country that deliver (at short range) bursts of x-rays and gamma rays lasting about as long as a nuclear weapon takes to explode, or one hundred-millionth of a second.

The largest of these machines is named Aurora and is located in the suburbs of Washington, D.C. The Aurora machine fills a concrete building about the size of a small airplane hangar, weighs 7000 tons (most of which consists of electric storage capacitors) and generates a gamma ray pulse of about 0.5 megajoules. Capable of irradiating whole missile stages at once, Aurora's gamma ray blast—which sounds like a muffled cannon—is, at a distance of a few centimeters, roughly equal to that of a 1-megaton antiballistic missile warhead at a range of 3 kilometers.

Neutron effects are of great interest too, and to duplicate them above ground researchers have relied since the 1950's on pulsed nuclear reactors.

Reactors produce no more than about 1 million low-energy neutrons in a single burst, and this is far smaller than the yield of some of the small, "neutron-enhanced" weapons of recent design. (A 1-kiloton explosion for example, can release about 10^{24} neutrons.)

For more intense bursts of neutrons, effects researchers are turning to particle accelerators. At the Los Alamos Meson-Physics Facility (LAMPF), the military side of ERDA is building a special target area for defense work called the Weapons Neutron Research facility. A less well advertised companion to LAMPF's highly publicized biomedical research unit, the WNR will, at $5.6 million, cost almost twice as much. According to congressional budget documents, the WNR would divert a small portion of the main accelerator beam to

Up the Need for University and Industrial Research

kilojoule laser would be needed to produce the gain needed for a power plant. By comparison, the largest lasers now operating produce about 1 kilojoule, and the $25 million laser under construction at the Lawrence Livermore Laboratory will produce 10 kilojoules at best. Furthermore, the numbers cited may be overly optimistic because certain plasma effects, which could reduce the energy gain, have not so far been included in the massive computer codes used to describe laser implosions.

In spite of the caveats in the report, James McNally of ERDA says, "I don't find it pessimistic at all. I regard it as very encouraging about the pursuit of the laser fusion research program." In fact, according to several people at ERDA, draft versions of the report included the assessment that laser fusion held more promise than the older approach, magnetically contained fusion.

The succinct 15-page report was the work of a four-man panel headed by Lawrence Hafstad, who previously managed reactor development for the Atomic Energy Commission (AEC) in the early 1950's and subsequently managed research and development for General Motors until 1969.

The Hafstad report was commissioned at least partially in response to the problem of KMS Industries, the Ann Arbor, Michigan, company whose progress in laser fusion research, without government funding and without access to government research, was something of an embarrassment to the AEC.

The thrust of the report is that government-sponsored research in laser fusion should be opened up, beyond the narrow base of the two ERDA weapons laboratories, at Livermore and Los Alamos, where it is almost exclusively carried out now. The report found that a larger portion of the R & D resources of the country could be tapped for laser fusion, and that such independent efforts would, through competition, enhance the scientific output and cost effectiveness of the weapons laboratories. It recommended that at least 10 percent of the budget for laser fusion be allocated for projects outside the principal ERDA laboratories, and that proposals for "external" projects should not be solely reviewed by the staff of the weapons laboratories.

Obviously referring to the 24 patent applications filed by KMS Industries which are being contested by the government, the Hafstad report recommended that ERDA should liberalize its administration of patents, saying that "The traditionally restrictive patent policy of the AEC, which may have been adopted for good reasons nearly three decades ago, has long been a serious handicap in getting effective industrial participation in programs intended for civilian use."

The recommendations to open up laser fusion research are now being implemented by ERDA, which recently awarded a limited contract to KMS Industries and is considering longer term proposals from several research establishments, including KMS and the University of Rochester.—W.D.M.