Fusion's $372-Million Mothball

Livermore wanted to be a contender in the race to design a commerical fusion reactor; but it lost without ever getting to turn on its big mirror machine

Livermore, California

PIGEONS flutter these days in the rafters above the largest and most expensive project in the history of Lawrence Livermore National Laboratory. And what was once the heady task of harnessing the power that fuels the sun and stars has become the more mundane job of keeping roaming gangs of experimentalists from cannibalizing parts from a gigantic still-born machine.

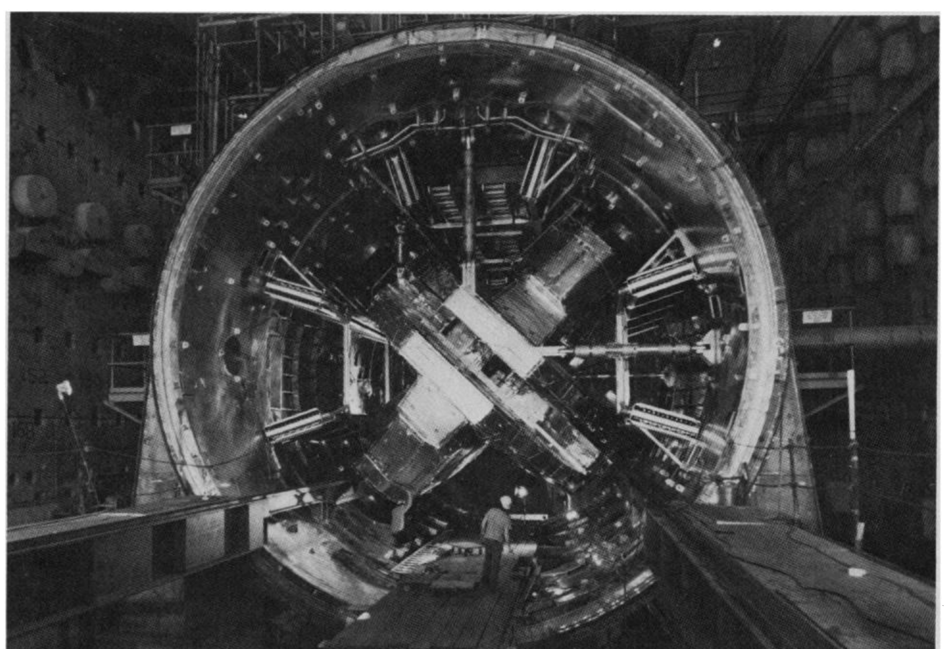
To its inventors at Livermore, the Mirror Fusion Test Facility (MFTF-B) was to be the machine that proved a design using magnetic mirrors could compete in an international race to produce a commercial fusion reactor. "We wanted to be a contender," says T. Kenneth Fowler, the project director at Livermore. It was Fowler's dream to use MFTF-B to propel his program into a real contest against Livermore's arch rival: the Princeton Plasma Physics Laboratory and its tokamak machine. But it was a race that was lost without ever being run.

On 21 February 1986, after 9 years of construction and $372 million, MFTF-B was officially dedicated. The ceremony was not a festive one. John Clarke, head of the Office of Energy Research at the Department of Energy (DOE), read what Fowler sarcastically refers to as "a dear Ken letter," wherein Secretary of Energy John Herrington commended Livermore's team on a job well done, but regretted that budget restrictions demanded the facility be "put on standby." Wrote Herrington: "This is frustrating and perhaps not the best use of national talent and resources, but we must bring the deficit under control." The news did not come as a complete surprise to the people at Livermore. As an act of charity, Clarke had leaked word of the machine's demise to Fowler in December 1985, giving researchers a chance to look for work elsewhere. MFTF-B was mothballed the day after its gloomy dedication. Says Fowler: "In my wildest dreams, or rather my wildest nightmares, I never envisioned it coming to this."

During the salad days, when budgets for energy research were rapidly expanding, who could have foreseen the complete collapse of the mirror program and the mothballing of all its experiments? After all, DOE has invested $775 million in the mirror program since 1974, of which $720 million has gone to Livermore. From a peak of $102 million in 1984, the budget for mirror research crashed to $9 million for fiscal year 1988. To paraphrase the country and western song: How could something that seemed so right turn out to be so wrong? For not only has MFTF-B collapsed—as the lead experiment at the lead laboratory, MFTF-B dragged all other mirror experiments down with it. In February, Livermore's $220-million Tandem Mirror Experiment-Upgrade (TMX-U) fired its last experimental shot after only 4 years of operation. This month, the Massachusetts Institute of Technology (MIT) will shut down its $30-million Tara experiment. Even the University of Wisconsin's small Phaedrus machine will probably be canceled next year. "There's just no future for the small stuff," explains Clarke of DOE. "The research, though interesting, can't go anywhere unless there's a big facility to scale up to." Says Richard F. Post, a veteran experimentalist at Livermore, "It's like a punitive act. They're squashing anything that has to do with mirrors."

Today, Post is compiling a history of the technical accomplishments of the mirror program. Yet the story of the rise and fall of the mirror machines would also make a proper tragedy. It contains many of the necessary ingredients: strong wills, great rivalries, fickle fate, and colossal waste.

The tragic scenes were played out against a background of shifting national priorities. During the story's run, there was first an energy crisis and then a budget crisis. The former poured dollars into energy research; the latter sucked them dry. In 1980, Congress passed an ambitious Magnetic Fusion Energy Engineering Act, which called for a fusion power demonstration plant by the year 2000, while in 1981 the new Reagan Administration was busy trying to dismantle DOE, the very agency charged with producing the fusion reactor. In keeping with the tragic theme, the protagonists of the mirror fusion program might also be said to have harbored the seed of their own destruction. "Tokamaks were getting way ahead of us. Mirrors needed a big push. So mirrors were pushed more aggressively than they should have been," explains Stephen Dean, former



Looking into MFTF-B. *Note the size of the men beneath the huge yin-yang coils at one end of the machine. The magnet fills the center of the vacuum vessel and is covered with liquid-nitrogen cooling panels.*

director of the magnetic confinement division at DOE and now president of Fusion Power Associates, an industry support group. Adds Jay Kesner, the theorist behind MIT's mirror facility: "The whole program was a gamble, a big gamble."

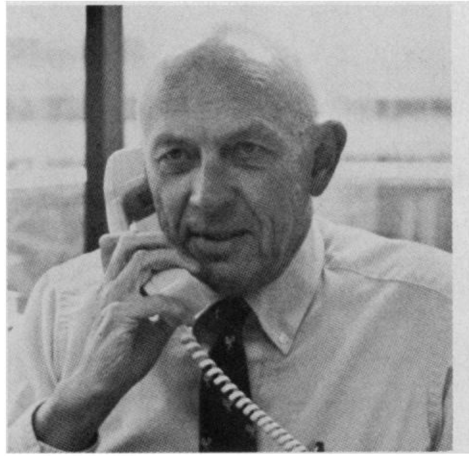
A visit to Livermore illustrates what Kesner means by big. "It's difficult to appreciate its size without standing underneath it," says William Pickles, a physicist at Livermore who spends his spare time giving tours of MFTF-B and keeping colleagues from unscrewing tempting components. There the machine sits, in Building 431, wrapped in a massive vault with walls of concrete 2 meters thick. You could literally drive a bus through MFTF-B's central cell, a stainless steel vacuum vessel 54 meters long and 10 meters in diameter. So huge is the vessel, in fact, that pumping MFTF-B down from atmospheric pressure takes 2 days. If the machine ever became operational, 150 people would be needed to tend to it. Its electric bill would run $1 million a month.

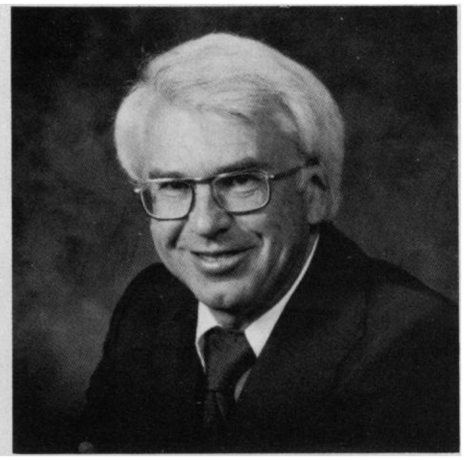
MFTF-B was to utilize pure deuterium, a heavy isotope of hydrogen, at temperatures of 150 million degrees Celsius, more than toasty enough to strip the deuterium atoms of their electrons and create the ultrahot ionized gas known as plasma, which would be held for periods lasting close to a second. These are aggressive goals, for they begin to approach the parameters needed for breakeven, a kind of touchstone in the fusion community, where the energy introduced to create and maintain a plasma equals the energy that would theoretically be produced by the fusion reaction itself.

It is the pernicious nature of plasma that it is extremely difficult to contain. One researcher describes plasma as "stellar Jell-O." At temperatures hotter than the sun's interior, plasma would destroy the walls of any vessel meant to hold it. The solution is to contain the gas within a powerful magnetic field. And it is here, over the geometry of containment, that the battle between Livermore and Princeton was fought.

MFTF-B was to contain its plasma within a long sausage-shaped central cell lined with a series of 12 superconducting magnets. At each end of the cell are six more superconducting magnets, in configurations shaped like baseball seams or wrapped around each other and dubbed yin-yang coils. As the name "tandem mirrors" suggests, these end magnets create thermal and electrostatic "plugs" that would act as "mirrors," reflecting the plasma particles back on themselves and keeping the fuel from leaking out of the ends.

The mirror machine is a radical departure from the design configuration most vigorously pursued by the rest of the world,





Betting on the come. *Edwin Kintner (left), then at DOE, bet that Kenneth Fowler (right) of Livermore could come up with a design for a commercial fusion reactor.*

including the European Community and Princeton. In all parameters, Princeton's Tokamak Fusion Test Reactor (TFTR) has led the fusion race in the United States. Unlike the open-ended mirror machines, the tokamak is a closed system, where the plasma is contained in a torus or doughnut-shaped vacuum vessel ringed with magnets. To inhibit a sideways loss of plasma caused by the curved field lines, researchers run a strong current through the plasma itself parallel to the field lines. But there were, and still are, inherent problems with the tokamak.

Edwin Kintner, for one, never liked tokamaks. The former associate director of DOE's Office of Energy Research is a nuclear engineer, not a plasma physicist. He admits he sees the world through the eyes of an engineer. Specifically, Kintner did not like the tokamak's geometry or the fact that tokamaks use a transformer, which forces them to operate in a series of pulses instead of steady state. "The pulse creates a large amount of stress, and no matter how well maintained, you don't have a long life in something that is always going on and off," says Kintner, now vice president of GPU Nuclear Corporation of Parsippany, New Jersey. As for the tokamak's shape, Kintner found its toroidal geometry an engineer's nightmare. "They're as bad as a pretzel," he contends. Mirror machines, on the other hand, with their long central cells, are easily accessible for maintenance. Their clean straight lines appealed to the engineer in Kintner. In addition, the mirror machines at Livermore would operate under steady-state conditions.

There was, however, one more reason for Kintner's support of the mirror design, and it was perhaps more important than anything to do with doughnuts and pulses and repairs. Kintner abhorred a one-horse race. "Everybody was concentrating on tokamaks," he says. "I thought it was necessary for these tokamak guys to have to look over their shoulders."

With Kintner receptive to mirrors, Livermore was in an ideal position to start lobbying for a big project, which it did with a vengeance. Under the direction of Post and his colleagues, the laboratory had produced a number of early mirror experiments that were encouraging. At each step, they pushed the geometry of containment toward more sophisticated and contorted shapes, all the while trying to overcome the bane of all open systems: the fact that they leak like a sieve. Through a string of relatively small machines—with names like Table Top, Toy Top, ALICE, and Baseball—researchers at Livermore discovered that beams of energetic neutral atoms could be used to build hot plasma and maintain it in a steady state. Unfortunately, they also discovered a problem that has plagued all fusion research: instabilities in the plasma. In the ALICE experiment, for example, when the researchers tried to push the plasma density above 10^9 particles per cubic centimeter, they found the plasma exhibited high-frequency instabilities. As density increased, more plasma leaked out of the system, an impossible situation for a potential commercial reactor.

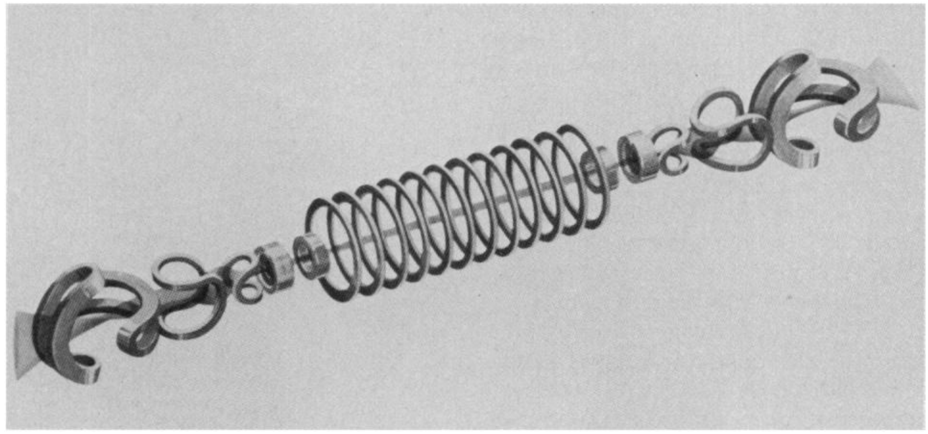
A partial solution was found in the 2XIIB machine in 1975. "A classic case of solving the problem by overkill," says Fowler. "You make the thing so powerful it has to work." In 2XIIB, they increased the neutral beam current a thousandfold over the power of earlier experiments. Some feared the neutral beams would self-destruct when they entered the seed plasma. Luckily, this did not happen. But something else did. With the increased temperatures provided by the neutral beams, density and containment time should have increased tenfold. They did not. Turbulence from microinstabilities had again thwarted the researchers, until Post and Fred Coensgen of Livermore hit upon the idea of stabilizing the main plasma by running a relatively warm, low-density plasma through it. The idea worked. What Livermore got was the hottest ***and*** densest plasma achieved at that time: 100 million degrees Celsius with densities of 10^{14} per cubic centimeter. "It made people sit up and take notice," Post says.

Livermore wasted no time proposing a huge scale-up of 2XIIB called the Mirror Fusion Test Facility (MFTF), the early version of what was to become MFTF-B. Fowler insisted there was no intermediate step between 2XIIB and MFTF. Not everyone agreed. Clarke, who then was a program director in the fusion energy division at Oak Ridge National Laboratory, remembers almost coming to blows with Fowler over the project. Clarke was against it because the proposed machine was not efficient. "2XIIB was a simple mirror. It was okay but too leaky. When they flooded warm plasma through the system, it got better. But it was still a long way from great, and MFTF was nothing more than a big scale-up of 2XIIB," recalls Clarke. "The *Q* was just too low." *Q* is the ratio between the fusion power produced in the central cell and the power needed to sustain the end plugs. As originally designed, MFTF's *Q* was around 0.5 at best. According to Fowler, a *Q* of at least 10 is needed for a commercial reactor.

The low *Q* did not stop Fowler and Kintner from pressing ahead. Fusion guru Marshall Rosenbluth, formerly at Princeton and now at the University of California at San Diego, informed officials at DOE that 2XIIB was a success. Though there was grumbling about the low *Q*, two review committees recommended that DOE fund MFTF. "Remember, this was all before high temperature success in the tokamaks," says Clarke. "People were saying, 'it's too early in the game to worry about reactors. Let's go ahead with MFTF and see what happens.' "

Kintner's decision to fund the device was a kind of a point of no return, for it established the scale of things to come. Kintner today still defends his decision: "If there was going to be a horse race, you had to have a horse and not a pony." MFTF was funded with the full understanding that no matter how efficient the Livermore team made MFTF, simple mirrors would never make an economically feasible reactor. This put Livermore under tremendous pressure to come up with ways to "enhance the *Q*."

Clarke remembers, "Kintner said, 'they're good people at Livermore, they'll figure something out.' " Indeed, there was a slogan heard often in Kintner's office at DOE. It was "betting on the come." Explains Clarke: "We were always betting that somebody would come up with a clever idea down the road." Ever the optimist, Kintner was also fond of quoting the father of the atomic submarine, Vice Admiral Hyman G. Rickover: "Where there is no vision, there is no future."



MFTF-B's magnet array. *"They kept adding one set of magnets a year until it collapsed under its own weight," says Lidsky of MIT.*

It was betting on the come that gave Fowler and Grant Logan, a young physicist who had come to Livermore from the University of California at Berkeley, time to invent an ingenious solution to the leaky design of MFTF. What they did was completely redesign mirror fusion. In 1976, Fowler and Logan decided that if two simple magnetic wells were connected by a long solenoid, the two wells could serve as tandem mirrors, holding the plasma fuel in the central cell, turning the positive potential of the plasma from a liability into an asset. (Simultaneously in the Soviet Union, a fusion researcher named G. I. Dimov hit upon the same solution.) What Fowler and Logan proposed was to simply turn the MFTF magnet on its side and use it as one end of a big tandem mirror machine. So was born the idea for MFTF-B. And so the price of the undertaking began to go through the roof.

To prove that the new design would work, Livermore got permission to build its Tandem Mirror Experiment (TMX). "When you've got a big machine, it plows ahead and it's easy to get smaller machines started," says Fowler. TMX proved that end plugs worked. By this time, Livermore had already spent \$150 million and MFTF-B had been designed twice. According to Clarke, the thinking at the time "was in for a penny, in for a pound."

Says Dean: "You've got to remember the historical context." The energy crisis had scared the federal government into giving DOE millions of dollars to spend on exotic energy research. "All kinds of ideas were bouncing around: solar, ocean, thermal, wind, synfuels. And we had only one design for a fusion reactor. The tokamak. What we wanted was a strong design to be number two," says Dean.

In 1980, Livermore decided it should redesign MFTF-B yet again. This time, Logan and David Baldwin of Livermore proposed adding another set of magnets to the end plugs and heating that plasma independently. In theory, this would allow a high electrostatic potential difference to be more easily created and sustained, thus plugging plasma leaks more efficiently. TMX was upgraded to test the "thermal barrier" concept, becoming TMX-U. "I tell my students that the mirror machines are like trees. A ring a year. You could tell how old they were by the number of magnets they kept adding to the end plugs. And they kept adding one set of magnets a year until it collapsed under its own weight," says Lawrence Lidsky, a professor of nuclear engineering at MIT who has criticized the fusion program for developing reactors when they should have been unraveling the underlying science first. Explains Post: "We had started with something that was straightforward and now we were getting more complex. This was making people on the outside wary. The physics was much more demanding—not only were we saying we're going to make a positive potential in the end plug, but we're going to make a negative potential right in front of it."

Because it takes so long to build big machines like MFTF-B, funding routinely begins while kinks in the project are still being worked out. To some degree, "betting on the come" is business as usual. Big experiments rarely move in a simple linear progression.

For example, Princeton's TFTR was initiated in 1976 even though an experiment to test the efficacy of neutral beams as heat sources did not provide conclusive support until 1978. "Leapfrogging is necessary if you're not prepared to sit on your hands for the next 5 years waiting for something to be built," says Harold Furth, director of the Princeton Plasma Physics Laboratory. But Furth adds that several experiments in the United States and abroad demonstrated that neutral beams would be effective for TFTR. "We knew very well that it would work. TFTR would not have gone ahead without knowing that," says Furth.

But at Livermore they were building a huge machine based on fundamentally new and untested principles. "They were stuck with having to build something on a large scale while at the same time trying to understand the basic physics," says Lidsky.

Says Fowler: "You could debate the decision, but it wasn't illogical. Building big machines is a mixture of lead times, resources, prudence, and gambling. The question to ask is: were our extrapolations reasonable or weren't they? We think they were reasonable." Clarke admits, "It was a high-risk experiment, but it wasn't totally crazy. . . . Each of these decisions seemed reasonable at the time."

Unfortunately, TMX-U was not wildly successful. Though confinement times were good, plasma density was low. It was difficult to get the density up. One problem was that cold ions would swamp the thermal barrier. Whether MFTF-B, with its own thermal barriers, would work any better than TMX-U is anybody's guess. The machine to test the principles sits in Building 431 at Livermore.

"No one believes MFTF-B would fail. But nobody is absolutely certain it would work either," says Dean. "It was a very risky kind of experiment performed on a grand scale. A major facility based on unfounded physics. People knew that going in," says MIT's Kesner.

Clarke's decision to close down the program at Livermore was a difficult one. "It would have been so much easier if I had a technical failure to point to," says Clarke. Faced with large cuts to the fusion program's budget, Clarke says that he was forced to slash mirrors to maintain stable funding for tokamaks. It was a tremendous blow to Fowler as well as Livermore. For years, the laboratory had been churning out a stream of proposals and reports, full of color photographs and drawings, loaded with hopeful timelines and filled with a language of optimism about the future of fusion energy.

As for the future of the mirror program now, there seems to be none. While a few at Livermore pretend to remain optimistic that MFTF-B will someday be put to use, it is a hope that will almost certainly be dashed. Because MFTF-B still lacks diagnostic equipment and additional heating elements, it would take at least another 18 months to make the machine operational. Fowler estimates it would also cost an additional $250 million to get worthwhile results from MFTF-B. This is a check that will never arrive. "We'll give ourselves a couple more years and then decommission the thing," Clarke says. As it stands, the machine costs $2 million a year just to keep in mothballs. Asked what would happen if his office were given another $100 million next year, Clarke answers that the money would go to tokamaks, not mirrors.

Fowler is resigned to the fact that it is again a one-horse race. This summer, Livermore began to uncrate and reassemble an old tokamak that DOE transferred from MIT to Livermore. MIT's Alcator-C machine now sits in a small alcove, dwarfed by MFTF-B. Hoping to use a free electron laser to drive the current in Alacator-C, Fowler and what remains of his team are joining other researchers around the world who are trying to make the tokamak a steady-state machine. "Now is the time to find out if the tokamak is a reactor or not, a time to resolve old issues, to either turn up or turn down the wick," says Fowler.

During the program's peak in 1984, some 500 people worked on the mirror project at Livermore. About 150 are left. Many who left the mirror program have gone on to other projects under Livermore's umbrella. More than a few are now involved in Star Wars research, for it is not a tremendous leap to go from fusion research to work on particle beam weapons. Of the 70 physicists who once worked for Fowler, about half remain. The others have moved on—to positions in small companies around San Francisco, to tokamak programs. One team hauled some of MFTF-B's diagnostic equipment to Japan and are now involved with GAMMA-10, one of the last of the mirror machines. Fowler and Logan are working on conceptual designs for the International Thermonuclear Experimental Reactor (ITER), a collaborative effort by the United States, the European Community, Japan, and the Soviet Union. A bitter pill, ITER is a tokamak.

The last holdout is Post, who has been working on mirror machines since 1952. Post refuses to work on tokamaks. His current project is yet another mirror machine, but unlike MFTF-B, this one would fit in the trunk of a car. Post's present research team involves not hundreds, but two graduate students. "It's not over yet," says Post. "It's possible neither tokamaks nor mirrors will turn out to be the one. In fusion, anytime you think you're right, you're usually wrong." ■

WILLIAM BOOTH

APS Panel Disowns Council Statement

Virtually all the authors of an influential report on laser and particle beam weapons, issued last April by the American Physical Society (APS), have taken the unusual step of publicly denouncing a statement by the APS council that was based in part on their own findings. They believe that the council's statement politicized their work and undermined its credibility.

The statement, which was issued the day after the report was made public in April, argued against early deployment of any elements of President Reagan's Strategic Defense Initiative (SDI), and said "the SDI program should not be a controlling factor in U.S. security planning and arms control." In making that argument, the council cited the panel's findings that directed-energy devices currently fall far short of the performance levels required for ballistic missile defenses and that at least a decade of intensive research will be needed to provide the technical basis for decisions on whether SDI systems based on them would be effective and survivable (*Science*, 1 May, p. 509).

In a letter published in the October issue of *Physics Today,* 14 of the 17 authors of the report state: "We object to being included in the council's statements on matters neither we nor they studied." Harvard physicist Nicolaas Bloembergen, who cochaired the panel that produced the report, says the panel scrupulously avoided statements that went beyond technical analysis of directed-energy technologies. "We had hours of debate to stop falling into that trap," he says. But the council's statement, he believes, undercut the nonpolitical nature of the report. "It was very embarrassing to members of the study group."

Val Fitch of Princeton University, the current APS president, says in a published response to the letter "in retrospect, it might have been better if the council had not restated some of the conclusions of the study panel. It was always intended that the DEW [directed-energy weapons] study stand clearly alone." He told *Science* that the council had been debating for 2 years making a statement on SDI, and said "it was a little unfortunate that the statement came out so soon after the report was released."

In any case, Fitch points out that although the report itself received widespread attention, the council's statement sank almost without trace. Press accounts at least had no difficulty separating the two and deciding which was the more important. ■

COLIN NORMAN