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激光玻璃-寻找聚变能的关键材料

Laser Glass - Key Material in Search for Fusion Energy

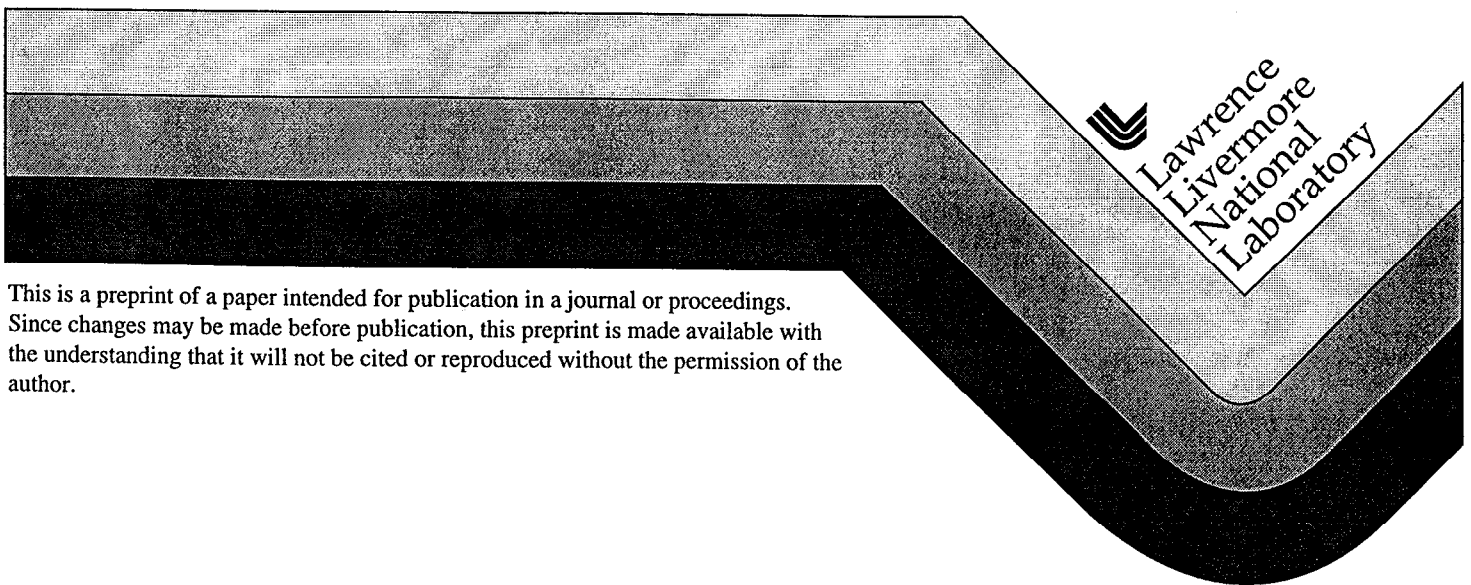
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PREPRINT


Laser Glass: A Key Material in the Search for Fusion Energy

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Text of Presentation for
Otto Schott Research Award Ceremony
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Lawrence
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Laboratory

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Laser Glass: A Key Material in the Search for Fusion Energy

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Abstract

Nuclear fusion is the energy source that powers the sun. For more than four decades man has sought to develop this essentially inexhaustible, clean power source for use on earth. Unfortunately the conditions needed to initiate fusion are daunting; the nuclear fuel, consisting of isotopes of hydrogen, must be heated to temperatures in excess of 100,000,000°C and maintained at that temperature long enough for the nuclear fuel to ignite and burn. Lasers are being used as one of the tools to achieve these conditions. The best lasers for this work are those that derive their energy from a unique set of optical glasses called “laser glasses”. The work to develop, manufacture and test these glasses has involved a partnership between university and industry that has spanned more than 25 years. During this time lasers used in fusion development have grown from small systems that could fit on the top of a table to systems currently under construction that are approximately the size of a municipal sports stadium. A brief historical and anecdotal account of the development of laser glasses for fusion energy research applications is the subject of the presentation.

Laser Glass: a material for the 21st century

Laser glass is a material that meets the challenge implied in the theme for the ESG conference: “Glass Science and Technology for the 21st Century”. Professor Snitzer’s presentation discussed glass fiber lasers and the great practical importance they will play in the world of fiber optic communications into the 21st century. The second major application of laser glass is the search for Fusion Energy as a power source for future generations.

Nuclear Fusion: energy source for the next millenium

It is important to distinguish between *nuclear fusion* and *nuclear fission*: Nuclear fusion is the energy source that powers the sun. For more than four decades man has sought to develop this essentially inexhaustible, clean power source for use on earth. In contrast, nuclear fission is the process that drives current nuclear power plants. In this process the atom is split into two smaller parts. The dominant atomic “fuel” for fission power plants is uranium. In contrast to fission, fusion combines two lighter atoms by fusing them into a heavier one. The fuel in this case is hydrogen or rather isotopes of hydrogen: deuterium and tritium. Deuterium occurs naturally in water at about the 0.017% level (about 1 part in 6000). Thus you often hear fusion scientists refer to the water in the ocean as an “inexhaustible” energy supply.

Figure 1 gives a schematic view of the fusion process. Here, the two isotopes of hydrogen (deuterium and tritium) undergo fusion reaction to yield a helium atom, a neutron and an enormous amount of energy (about 17 MeV). Einstein was the first to quantify the amount of energy such a reaction would generate using his famous equation: $E = mc^2$. Here E represents the energy produced during the nuclear reaction and c is the speed of light. The quantity m is the difference in mass between the starting materials (D+T) and the products (He+n). The mass change during a fusion reaction is rather small but c^2 is a very large number so the energy released turns out to be very large. In fact, one gram of hydrogen nuclear fuel generates about the same amount of energy as 2400 gallons of oil, enough energy to drive a car roughly 100,000 km.

Unfortunately the conditions needed to initiate fusion are daunting; the nuclear fuel (i.e. hydrogen isotopes) must be heated to temperatures in excess of 100,000,000°C and maintained at that temperature long enough to ignite and burn (in a nuclear sense). The problem of achieving fusion energy then comes down to developing a method to simultaneously heat the fuel and hold it together for a time long enough to react. There are three known ways this can be done:

- (1). Gravitational Confinement - the method for fusion energy generation by the sun.
- (2). Magnetic Confinement - here magnetic fields are used to confine the charged particles associated with the hot nuclear fusion fuel.
- (3) Inertial Confinement Fusion - the method we are pursuing at Lawrence Livermore National Laboratory (LLNL) where the fuel is compressed using high-intensity laser beams that simultaneously heat as well as confine the nuclear fuel.

The Inertial Confinement Fusion (ICF) concept

Figure 2 illustrates the ICF concept. Here a series of laser beams uniformly illuminate the surface of a tiny hollow plastic or glass capsule that contains the hydrogen isotope fuel. The capsules in use today are only a few hundred microns in diameter, in other words, no larger than a grain of sand. The laser beams rapidly heat the surface of the capsule causing the outer surface to blow-off. This rapid blow-off in turn compresses the fuel and heats it. During the final stage of compression the hydrogen fuel at the center of the capsule reaches a density nearly 20 times that of lead, and a temperature of 100,000,000°C. At this point the fuel “ignites” and a thermonuclear “burn” spreads rapidly from this central ignition spot into the surrounding fuel. The energy output from the fusion reaction is up to 100 times greater than that input by the laser.

John Nuckolls (LLNL) was the first to propose the ICF concept of using lasers to drive fusion reactions; this was in 1961, the same year that Prof. Snitzer demonstrated the first glass laser. Early researchers at LLNL used lasers powered by synthetic rubies. However as the systems grew larger and more powerful ruby lasers became impractical. The use of glass lasers for ICF research became popular beginning in about 1970 and soon systems were in operation in the US, France, UK, and Russia. Since that time a series of larger and larger lasers have been built to investigate the fundamental physics of the capsule implosion and the ensuing fusion reactions. To date none of these lasers has been large enough to achieve ignition. Note that fusion reactions *have* been detected,

often in significant numbers, but never enough to indicate that the fuel has ignited. Perhaps the best way to visualize the level of progress is with a simple analogy. Suppose one wishes to ignite a piece of wood using a torch. If the torch is only briefly applied to the wood then the wood begins to char and generate smoke but it will not ignite. On the other hand, if the torch is held on the wood for a long time then eventually it will ignite and a flame will be produced. Similar to this analogy, our current lasers are able to produce “smoke” indicating that fusion reactions are occurring but these lasers can not supply enough heat to achieve ignition.

The LLNL Nova laser

The lasers that have been built thus far range from small systems that can fit on a table to large system that require an entire building to contain the laser hardware. LLNL’s Nova laser is approximately the size of a football field. Figure 3 is a view of Nova’s main laser bay; for scale notice the man standing in the center of the photo. This laser was completed in 1984 and consists of 10 separate laser beams. All 10 laser beams are fired simultaneously and propagate to the target chamber (Fig. 4). Inside this 3-m-diameter chamber is the tiny, grain-of-sand-sized target discussed earlier. Figure 4 shows where five of the beams enter the chamber through cylindrical tubes that are attached to the chamber wall; the other five beams enter from the opposite side.

Laser Glass: the heart of the laser

For many years LLNL has investigated which optical materials make the best lasers for fusion research. This research has shown that presently lasers using neodymium-doped glasses give the best performance for ICF applications. Professor discussed the glass laser oscillator and how it can be used to generate a single pulse of light. Here we discuss the method for amplifying such a pulse to a much higher energy (see Figure 5). A large plate of Nd-doped laser glass rests in the center of a box that serves as the amplifier. Four of the walls of the box are lined with flashlamps plus a set of silver-coated reflectors that direct the flashlamp light to the laser glass. One can think of these lamps as simply flash bulbs similar to those used with a camera (but much larger). Just as one “charges” a camera before taking a flash picture we also charge large electrical storage units (capacitors) that are then used to drive these lamps. When the laser is fired, it triggers the flow of this electrical energy to drive the flashlamp. The light from the flashlamps is captured by the Nd ions contained in the laser glass and is temporarily stored there. If you were able to use a special viewer to peer inside the amplifier box as the lamps fire you would actually see the laser glass fluoresce thus indicating that the Nd ions had captured the flashlamp light and converted it to stored energy within the glass.

Shortly after the flashlamps fire, a weak laser pulse (generated by the oscillator Prof. Snitzer described) is propagated down a beamline that contains the laser glass amplifier (see Figure 5). As this pulse passes through the laser glass it stimulates the release of the stored energy thus amplifying the weak input pulse.

Figure 6 shows an example of one of the large Nova laser glass amplifiers. The lasers used for fusion research contains many such amplifiers stacked one after the other.

The overall increase in the initial pulse energy after passing through all the amplifiers can be very large. For example the increase in energy (i.e. gain) is about 10^{14} for Nova.

So why is laser glass such a good material for use in ICF amplifiers? There are three key reasons:

- (1) It can store the flashlamp energy at high concentrations,
- (2) The stored energy can be efficiently extracted with a transmitted laser pulse as shown in Fig. 5,
- (3) Laser glass can be manufactured in large sizes, at comparatively low cost, and with very high optical quality. By high optical quality we mean the glass is highly homogeneous and free of internal defects. Note that at the very high energies generated by the laser, any defects, such as solid inclusions, will explode and fracture the glass.

Laser glass leads to a unique partnership

When Professor Snitzer made the first glass laser in 1961 he had to literally do everything himself: build the laser hardware, make the flashlamp source, make the laser glass, and then get the whole contraption to work; an amazing feat! His first laser used a very small piece of laser glass; in fact, it was just a fiber. Maybe this was the first indication of just how difficult this glass is to manufacture!

In the “early” days of glass lasers nearly every major glass manufacturer was involved in making laser glass. Of course there was Prof. Snitzer’s organization, American Optical Corp., but also Corning, Kodak and Owens-Illinois to name but a few. Most of the manufacturers supplied glass just for scientists because lasers were still mainly a curiosity rather than a commercial product. Evaluating a particular laser glass was quite difficult in those days. A researcher had to order a glass, have it manufactured to a given size and specification (or even make it themselves), then install it in a laser to determine its performance. This was a laborious, time-consuming process.

By the time the laser fusion program began in the early 1970s, it became clear such an approach was impractical in the search for better laser glasses. In 1972, LLNL was fortunate to hire a physicist, Dr. John Emmett, who turned out to be a true visionary in the development and construction of large glass lasers. Emmett, although a physicist, loved optical materials and materials research. He realized that if there were to be a successful fusion program it would require the partnership of laser physicists, optical glass manufacturers, and laser hardware builders. This is nearly identical to the approach Ernst-Abbe, the physicist, Otto Schott, the glass chemist, and Karl Zeiss, the instrument builder used nearly a century earlier.

Emmett contacted several companies; but to be brief, two main companies became the key players in the development of laser glass for ICF applications: Schott Glass Technologies (Duryea, PA) and Hoya Corporation (Tokyo, Japan). This partnership with the optical glass industry that Emmett started nearly 25 years ago remains intact today.

A search for the best laser glass: three “generations” of scientists

When Emmett came to LLNL in 1972 he brought with him another young physicist, Dr. Bill Krupke. Krupke showed that it was possible to evaluate how “good” a laser glass was by making a few simple measurements of a small glass sample. In other words, it was no longer necessary to make optical quality glass and then install it in a laser to test it. The measurements that needed to be made using Krupke’s method were rather straightforward and glass chemists could easily perform them to evaluate various glass compositions. As a consequence there was an explosion of glass composition studies as well as an investigation into the more subtle features that affect laser glass performance.

The first question glass chemists and laser physicists faced is which glass type would work best for laser fusion applications. The “first generation” of scientists to look into this was led by Marv Weber (LLNL), Norbert Neuroth (Schott Glas, Mainz), and Tetsuro Izumitani (Hoya). In addition, Steve Jacobs (University of Rochester) and Charles Rapp (Owens-Illinois) were also key players (of course there were many others too).

Weber was particularly prolific and investigated a number of glass types including silicates, phosphates, fluorophosphates, fluorides, chalcogenides, tellurites, chlorides, etc. He also established a program for characterizing many of the optical and laser performance properties of these glasses. Weber’s counterparts at Schott, Hoya and Owens-Illinois produced the first set of commercial laser glasses specifically formulated for use on fusion lasers and these were installed on an LLNL laser called “Shiva”.

About five years later (~1980) a “second” generation of scientists began to work on laser glasses (Stan Stokowski [LLNL], Alex Marker and Lee Cook [Schott], and Yoshi Toratani [Hoya]). Laser glass R&D now began to shift away from the search of a broad range of glasses and instead focused on given glass types. Stokowski et al. published an extensive catalogue of laser glasses and their properties; this catalogue remains in use today. Many of the catalogue glasses were prepared by Schott and Hoya.

By the mid-80s, when I joined the laser glass group at LLNL, it was realized that phosphate containing glasses (as opposed to the more common silicate glasses) were the best overall glass type for use in laser fusion applications. Joe Hayden (Schott) joined the laser glass effort at about this same time and he, Alex Marker and my colleagues and I at LLNL collaborated extensively on studies to optimize phosphate laser glass compositions for ICF. We also carried out similar collaborations with Izumatani, Toratani and Kunio Takeuchi at Hoya.

The problem of platinum inclusions

The year 1985 was a low point in the development and production of laser glass; platinum inclusions were found in the laser glass that was manufactured for the Nova laser. These inclusions, only a few microns in size (about the size of a human blood cell) exploded when illuminated at high powers and soon made the laser glass unusable. There was great fear that this problem, which at that point had gone unsolved for more than 20 years, would spell the end to the laser fusion program.

In a remarkable collaboration among researchers at LLNL, Schott and Hoya, we developed a process that allowed us to dissolve platinum inclusions in the glass during its manufacture. We also put in place an inspection technique that used a laser to scan each glass piece to verify that it did not contain platinum inclusions. Using this technology, all the Nova glass was re-melted and replaced. Thus for the first time in the history of laser glasses a manufacturing process was available that gave inclusion-free glass. This process is extensively used today and glasses manufactured by this technology are in use in all the high power fusion lasers throughout the world (France, Japan, Britain, China, Russia and the U.S.).

As a happy ending to this story, Nova has been using this glass for more than 13 years and there has been no damage problem. In fact, Nova has been such a successful system that the results from the fusion energy research conducted using this facility has been instrumental in the decision to proceed with the next generation of lasers.

The National Ignition Facility (NIF)

The results from Nova showed that in order to achieve ignition we would need to build a laser with output energy approximately 20 times greater. This laser system and target facilities is known as the National Ignition Facility (NIF): it is so named because of its main goal to achieve fusion ignition and because it is considered to be a national research facility within the United States.

In contrast to Nova's ten beamlines, the NIF contains 192. Moreover the design of the NIF is a dramatic departure from that of Nova. To verify that this new laser design would work, beginning in 1991 we built a prototype of one of the beamlines; this prototype laser was completed in 1994 and successfully operated to the full NIF design specification. Key to its design was the use of plates of Nd-doped phosphate laser glass nearly 1 meter long and 0.5 meter wide and about 4 cm thick. Each of these plates is more than twice the size of the largest pieces made for Nova.

Figure 7 gives an artist's drawing showing the NIF as it will appear when completed. Figure 8 shows the actual NIF construction site on about June 1 1999. Construction of the NIF began in 1997 and is scheduled for completion in 2003. The building that houses the laser will be completed by about 2001. In early June we moved the 10-m-diameter target chamber (that weighs about 170 metric tons) into place within the target bay. The chamber is so large that we literally must build the rest of the building around it after it has been moved.

Our industrial partners for the NIF laser glass, Schott and Hoya, have again risen to the occasion. The NIF will require about 3500 plates of high optical quality laser glass having a mass of more than 150 metric tons; if the glass plates were stacked end-to-end they would cover a distance of more than 3km. This is more than 10 times the quantity of glass that was used on Nova. The only method for producing this glass in the time required for NIF is by continuous glass melting. This again is in sharp contrast to the method used for Nova where each glass piece was manufactured one-at-a-time, with one melt making one glass plate.

Continuous melting of laser glass for the NIF has begun at both Schott and Hoya and both companies are scheduled to begin shipping laser glass this month (June 1999). The total NIF production will last nearly three years. Although the continuous melting and forming of the laser glass occurs quite rapidly, the post-melt processing, such as fine annealing, scanning for inclusions, and measuring the optical homogeneity (that is, the lack of distortions within the glass) proceeds at a slower pace. Our goal is to ship finished glass at the rate of about 1000 plates per year.

Apart from the NIF presently under construction at LLNL, the French Commissariat a l'Energie Atomique (CEA) is planning to build a similar laser called "Laser MegaJoule" (LMJ) near Bordeaux. The LMJ is planned to have as many as 240 beamlines and require nearly 4500 laser glass plates having a mass of nearly 200 metric tons. As soon as Schott and Hoya complete the glass production for NIF they will then begin an additional 3-year production cycle of laser glass for LMJ.

The technical challenges of continuous melting laser glass are many and time does not allow for such a discussion. Suffice it to say that LLNL has worked with both Schott and Hoya over the last five years to develop the laser glasses and the melting process, design the melter, build the buildings to house the production systems, install the melters and carry out test operations. Our colleagues at CEA have been financial participants in all of these activities. Otto Schott would have been proud to see such a unique collaboration between the glass industry and the University in this quest for fusion energy.

Visual summary of progress in laser glass

The glass technology needed to meet the needs of ICF lasers has improved dramatically over time. Figure 9 illustrates this with a comparison of the various size pieces of laser glass manufactured over the last 25 years for use in LLNL's ICF lasers. Also shown for comparison is a piece of laser glass the same size as that used by Snitzer in his first laser in 1961; it is a glass fiber about 300um in diameter (about three times the thickness of a human hair) and 7.5 cm long

On the left side of the figure 9 are shown the small laser glass disks that were manufactured for LLNL's first glass laser: Janus. Janus was soon followed by Argus and then Shiva, each of which required more disks of a larger size. Roughly ten years after Shiva, the Nova laser was built and the glass type was changed from silicate to phosphate because of the much-improved performance of the latter glass. As discussed previously, we also invented a process for making phosphate glass free of inclusions.

In 1992 we built the NIF prototype laser (called "Beamlet") that required rectangular plates of glass nearly twice as large as Nova (Fig 9). It is interesting to note that one NIF/Beamlet glass plate contains more glass than the entire Janus laser!

The NIF laser glass is nearly identical in size to that of Beamlet however we require about 3500 and CEA about 4500 individual glass plates. As stated above, continuous melting of laser glass will be used to produce this glass. The gentleman shown in Figure 9 is holding a piece of glass that was cut from a strip of laser glass produced by

continuous melting. This glass strip is formed as the molten glass exits the melter and reaches a length of approximately 30 meters as it travels through the annealing lehr. Plates of laser glass roughly one-meter-long are then cut from this strip as it exits the lehr.

Acknowledgements:

I have been very fortunate to spend my professional career at LLNL, much of that time working on ICF and laser glass. At LLNL I've had the opportunity to work with many of the great names in the field of laser glass and to them I owe a great debt; particularly Steve Payne, Stan Stokowski, and Marv Weber. Of course the collaborations with my colleagues at Schott Glass Technologies and Hoya Corporation have been a very rewarding experience; in particular, my sincere thanks to Alex Marker, Joe Hayden, Yoshi Toratani, and Kunio Takeuchi for your friendship and your outstanding technical contributions. In addition, a number of colleagues at LLNL have had a strong impact on my career and to them I am grateful; specifically Mike Campbell, John Emmett, and Eric Storm. Finally, I am deeply indebted to the members of the NIF Laser Glass group; particularly my young colleague Tayyab Suratwala (the "fourth" generation of laser glass scientists) and our outstanding group: Chuck Thorsness, Paul Ehrmann, Rusty Steele, Mark McLean, Sara Kassahun, Andrea Flammini and Alene Clasen. And, of course, thank you Prof. Snitzer for starting it all!

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Figure Captions

Figure 1. Fusion refers to the process of combining lighter atoms to make a heavier one. Shown here is the fusion reaction of two hydrogen isotopes (deuterium and tritium) to form a helium atom and a high-energy (14 MeV) neutron. During this reaction some mass is lost that, according to Einstein's famous equation ($E = mc^2$), is converted to energy.

Figure 2. The four steps of the Inertial Confinement Fusion (ICF) process: (1) laser surface heating, (2) capsule blow-off and compression, (3) ignition, and (4) thermonuclear fusion burn.

Figure 3. View of the laser bay of LLNL's Nova laser. The intense laser beams that are used to drive the fusion capsules are generated in the hardware shown to the right and left of the person shown in the figure.

Figure 4. The Nova spherical target chamber. At the center of this 3-meter-diameter chamber is the tiny fusion fuel capsule. The five structures attached to the walls of the target chamber are the entry ports for 5 of the 10 beams of Nova. The other 5 beams enter on the opposite side.

Figure 5. Schematic representation of the manner in which laser glass stores light energy emitted by an electrically driven flashlamp and then releases this stored energy to a weak transmitted pulse. The weak pulse stimulates the release of the energy stored in the glass and, in the process, is amplified.

Figure 6. Photograph of a Nova amplifier showing the wall of flashlamps and silver reflectors that surround the two laser glass disks. The beam that is to be amplified enters through one end of the box and, after passing through the laser glass, exits the other end. Note that the slabs are mounted at an angle (Brewster's angle) within the amplifier box.

Figure 7. Artist's rendering of the National Ignition Facility (NIF) presently under construction at LLNL. The NIF will use 192 separate laser beams to drive capsules containing liquid deuterium and tritium to conditions for fusion ignition. The laser requires about 3500 plates of laser glass that are used to produce the output energy needed to drive the capsule. When completed the NIF will be about the size of a small sports stadium.

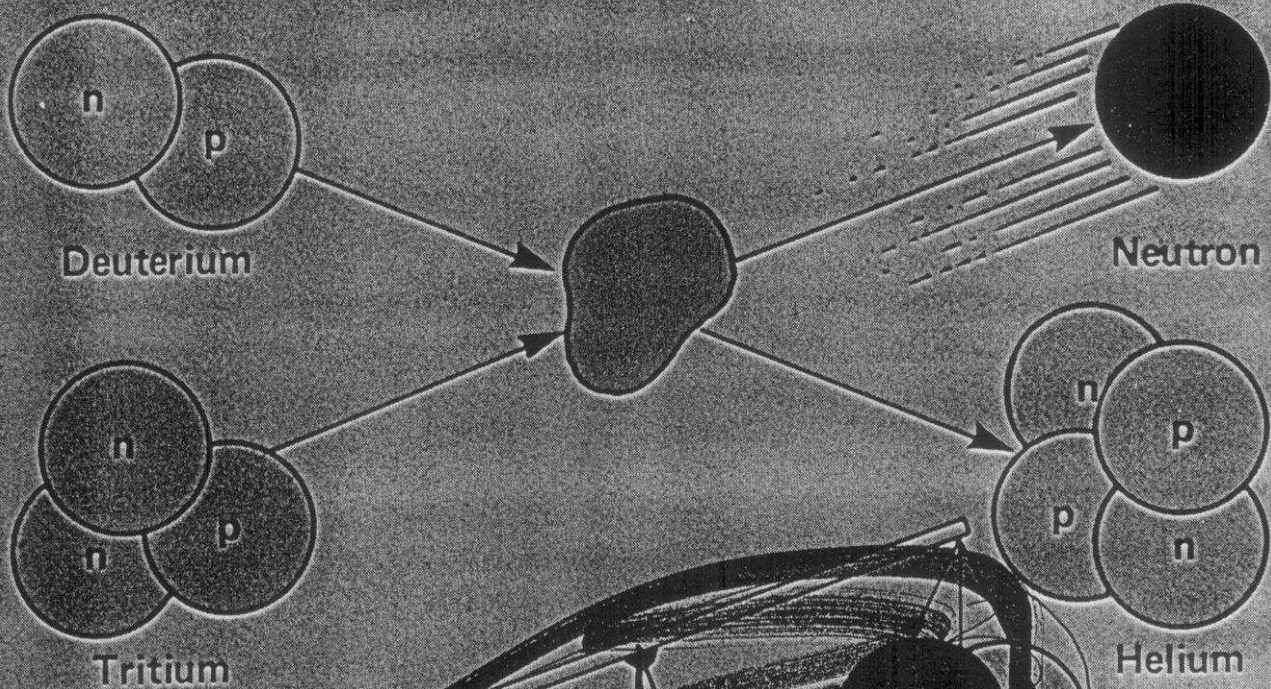
Figure 8. View of NIF construction in April 1999. Shown is the building that will house the 192 lasers and the target chamber area where the fusion ignition experiments will be conducted.

Figure 9. A visual comparison of the laser glass elliptical disks and plates that have been melted for various LLNL laser systems constructed over the last 25 years. In about 1983 we first began the use of phosphate glasses. Continuous melting was demonstrated for the first time in late 1997.

D-T FUSION REACTION

Produces Helium, a neutron and 14 MeV

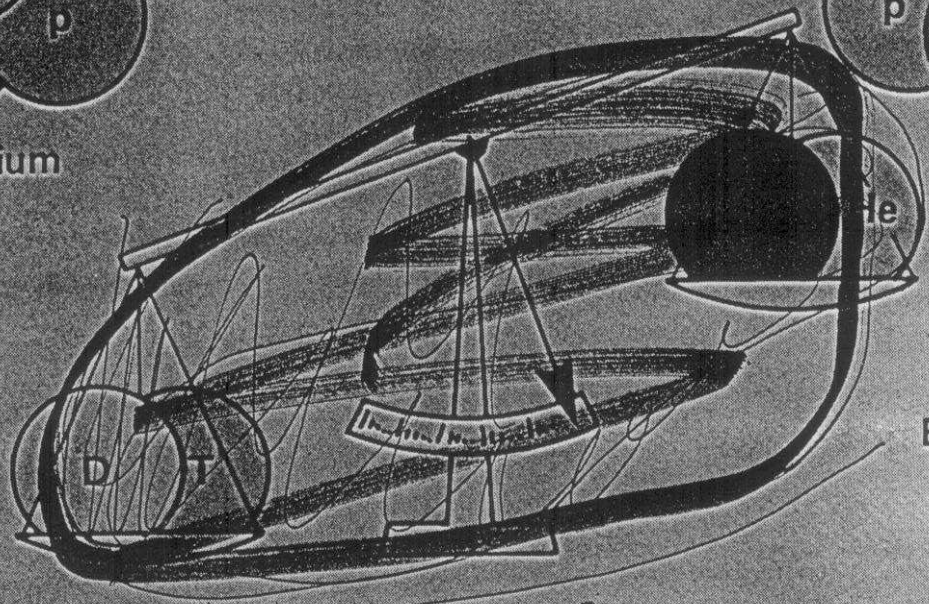
Energy 



+ 14 MeV

M_1

M_2

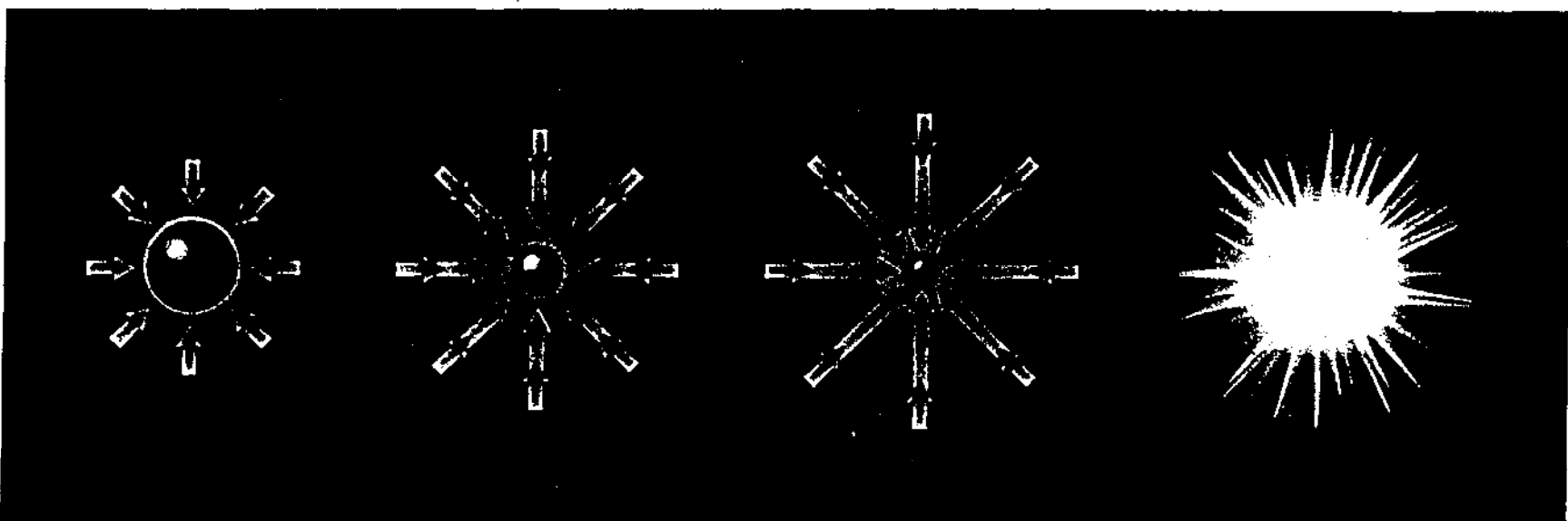


$$E = (m_1 - m_2)c^2$$

Fig 2



Four stages of the inertial confinement fusion process



Atmosphere Formation

Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Compression

Fuel is compressed by rocket-like blowoff of the hot surface material.

Ignition

During the final part of the driver pulse, the fuel core reaches 1,000-10,000 times the density of liquid DT and ignites at 100,000,000 C.

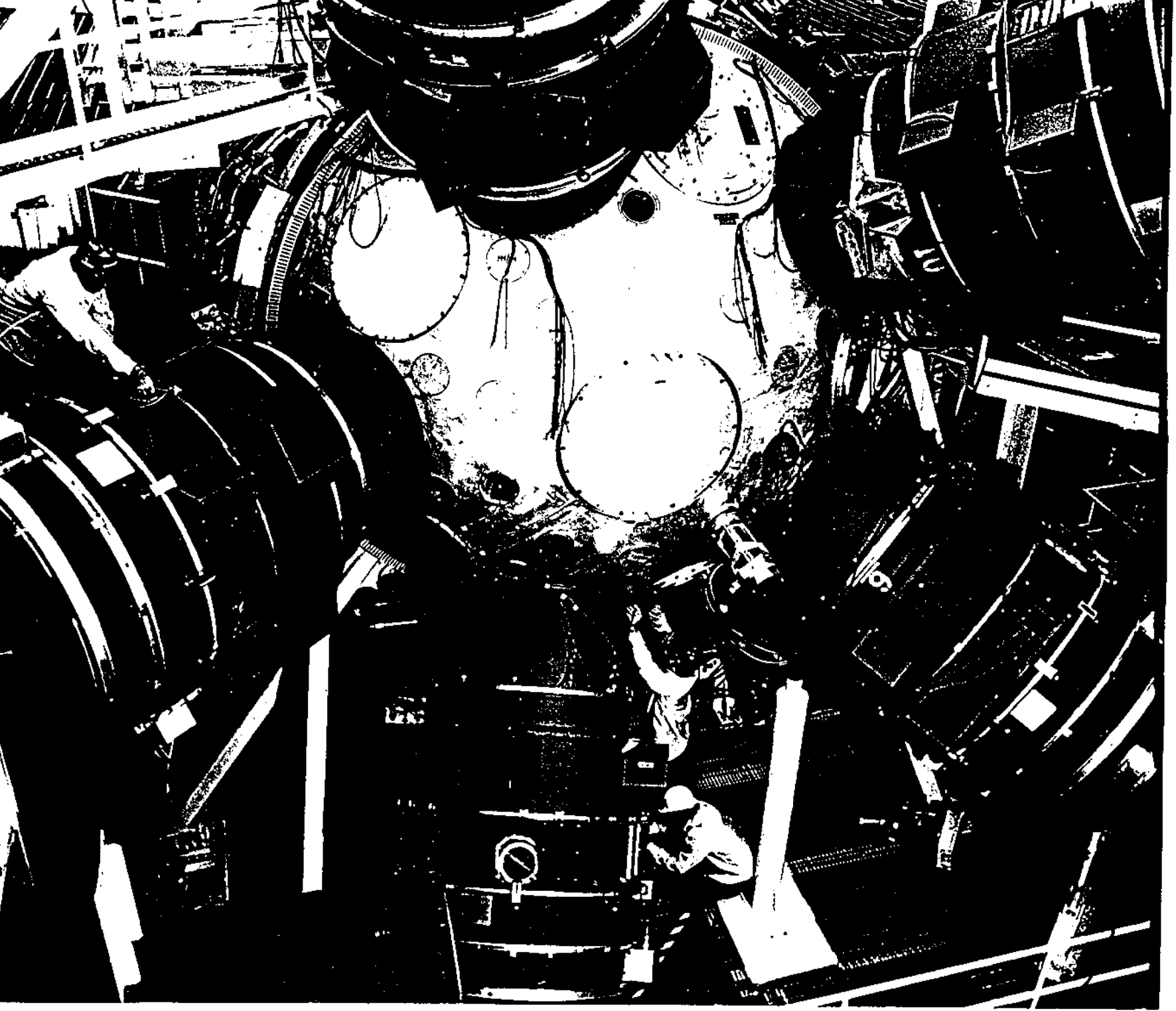
Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy.

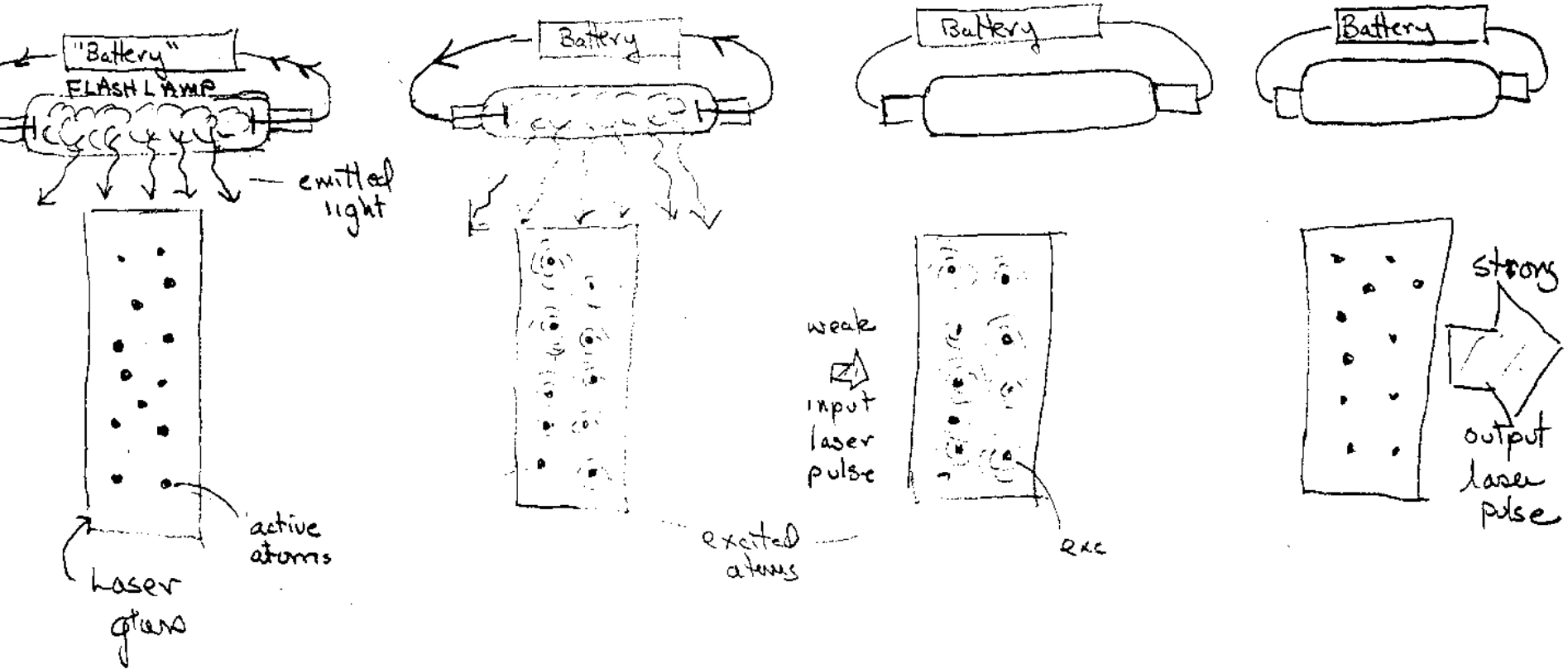
Fig 3



Fig 4



Description of how laser glass "works"



Flash lamp fires producing white light output

2. atoms absorb light and become excited

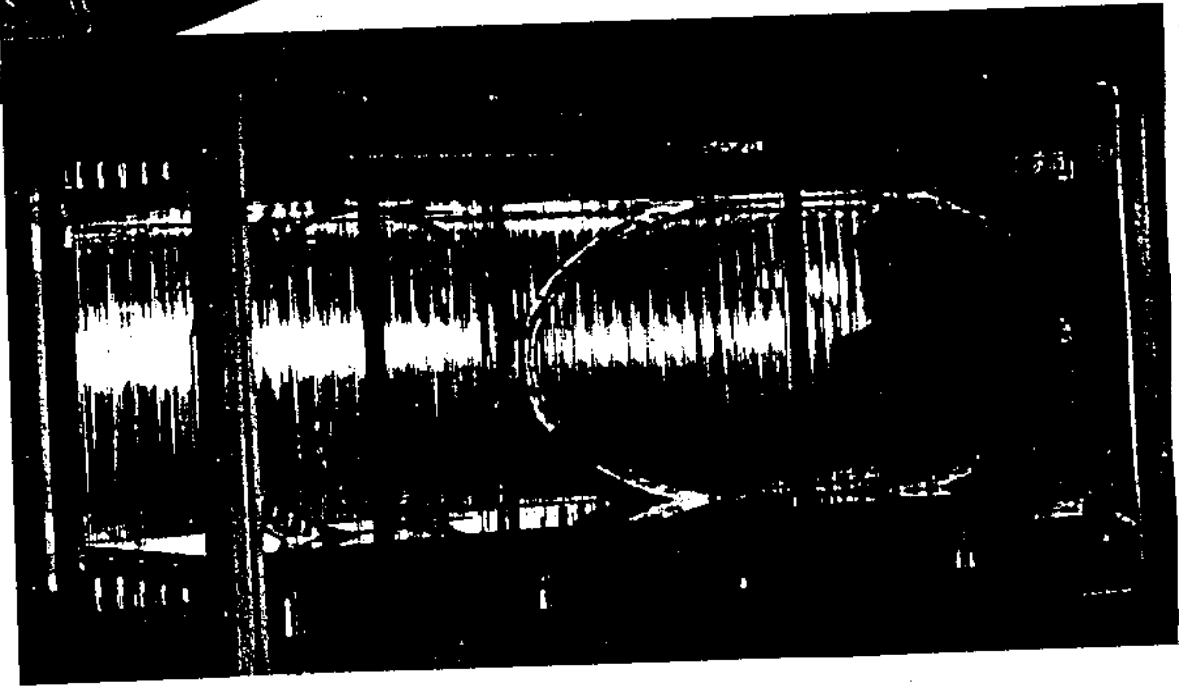
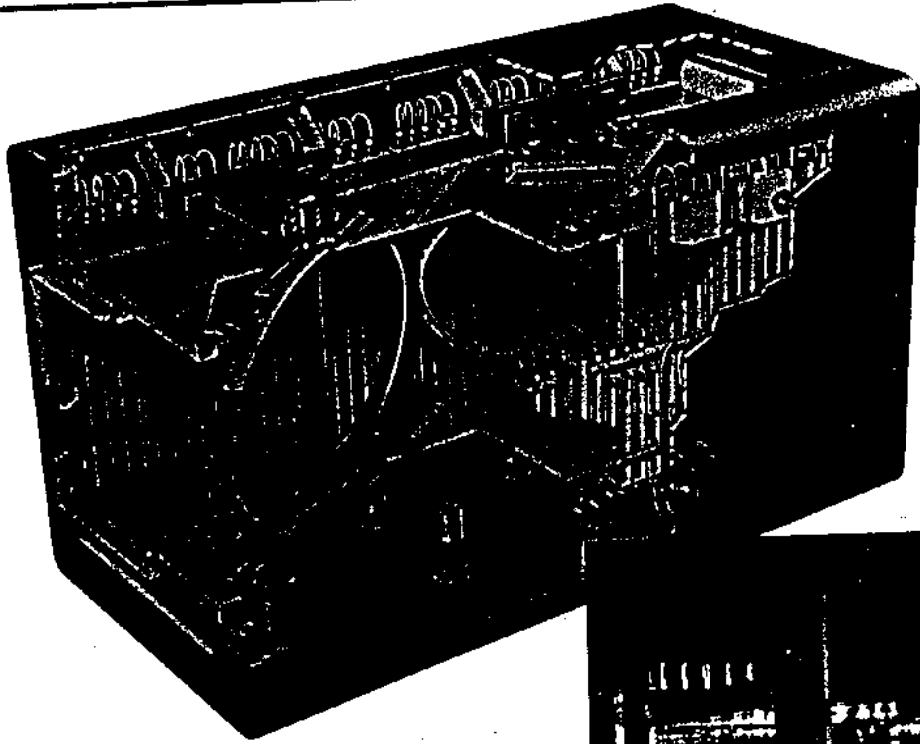
3. weak pulse enter glass

4. excited atoms give up energy to pulse making it strong

Fig 6

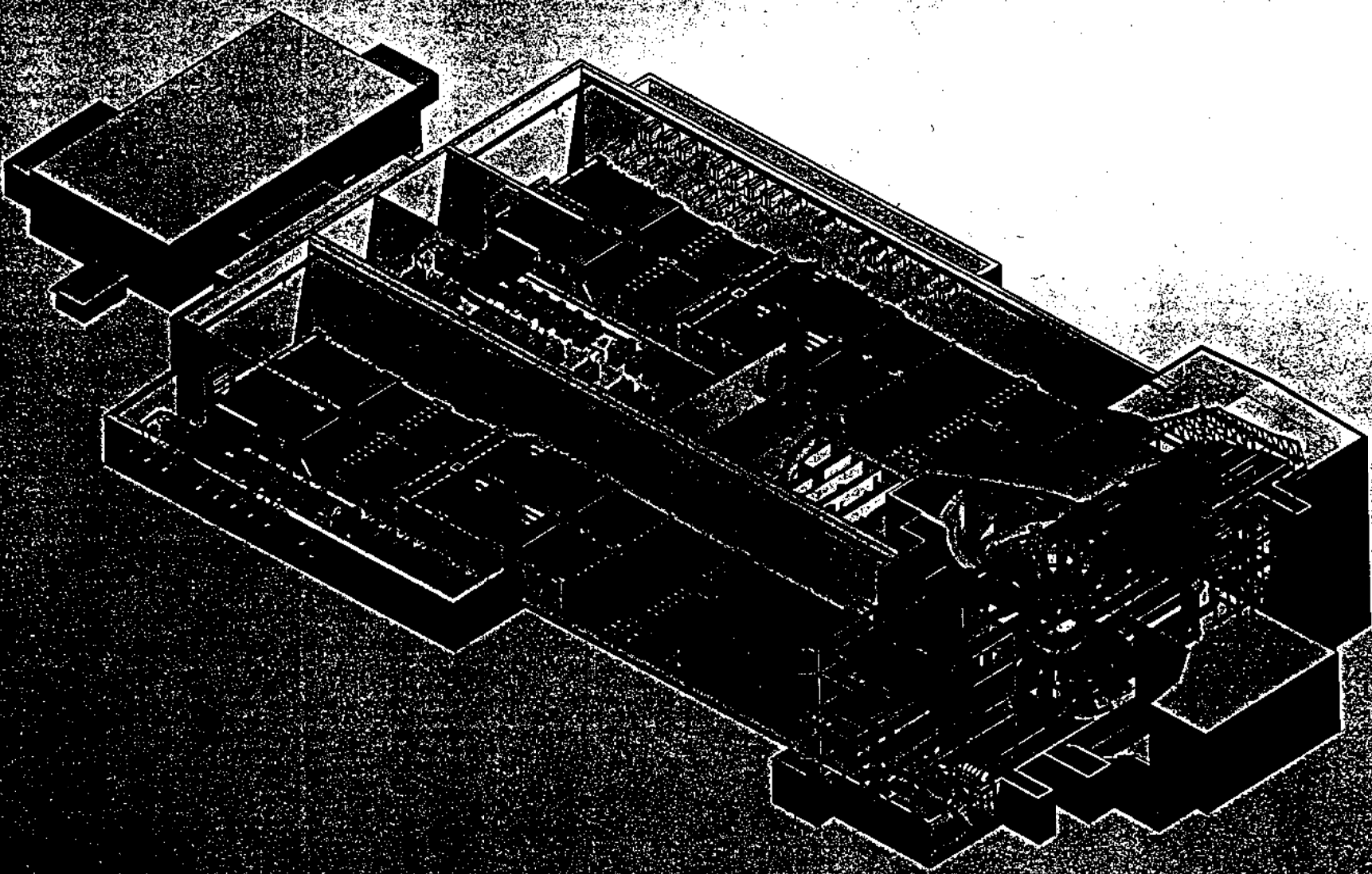


Nova's large amplifiers contain two laser glass disks surrounded by flashlamps



40-00-0798-1455
1JHCeld

Fig 1



Aerial photograph of NIF construction—1/13/98

Fig 8

NIF

The National Ignition Facility

need updated
NIF photo!

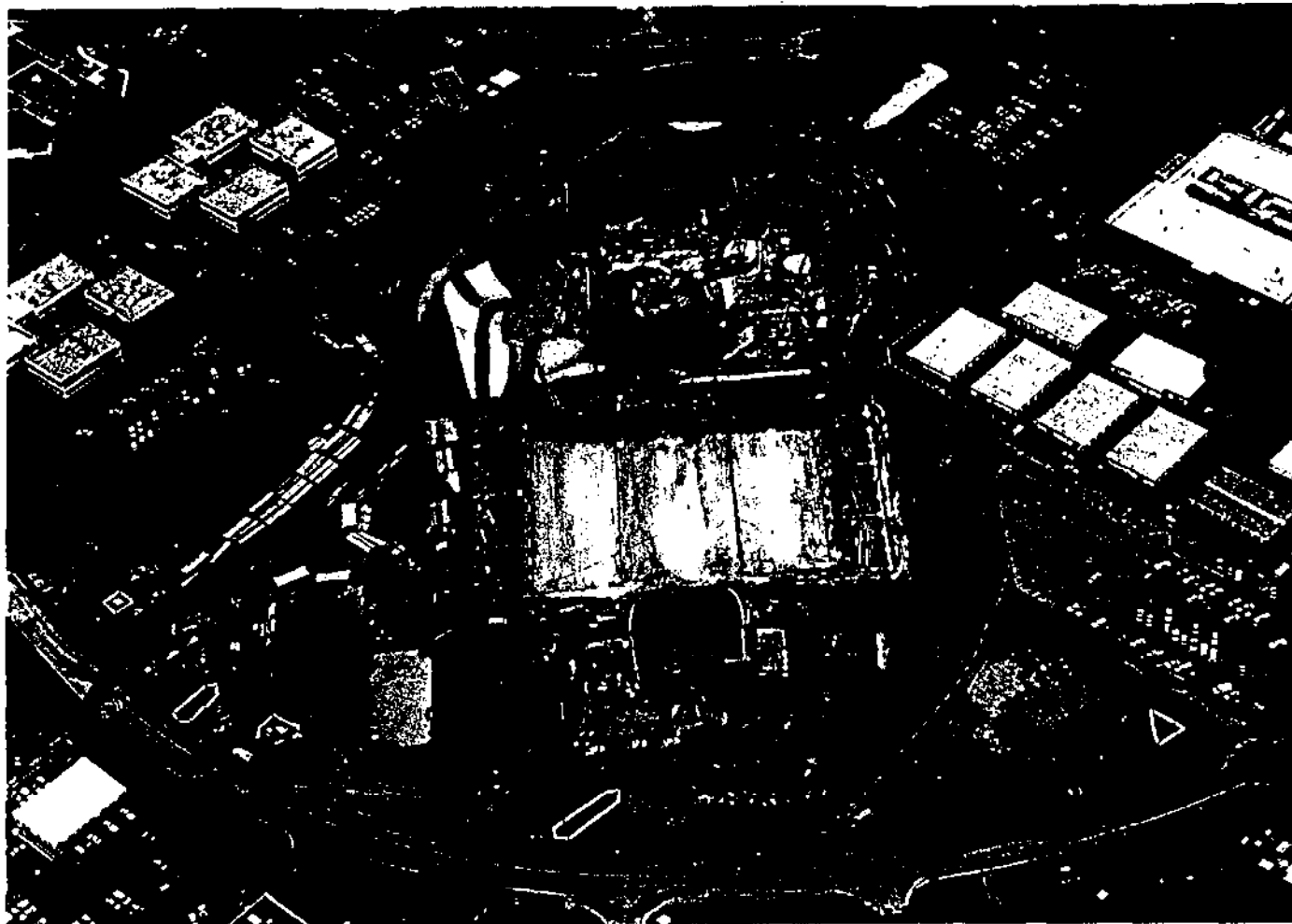


Fig 9

Laser glass technology has changed dramatically in the last 25 years

