UCRL- 93568
PREPRINT

UCRL--93568

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DE86 002854

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This Paper Was Prepared for Submittal to
Seventh International Workshop on Laser
Interaction and Related Plasma Phenomena
Monterey, CA
October 31, 1985

October 1985

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A MULTIUSER DEVELOPMENT SCENARIO FOR ICF*

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INTRODUCTION

Concern has been expressed in recent years that the development of fusion power may require a series of facilities that are so expensive as to be unaffordable even if the end design of a power station appears to be attractive. Of course, the perception of what is affordable depends a great deal on the national urgency attached to the program at any given time. Just a few years ago, after a decade of fuel shortages, gas lines, and the energy "crisis", Congress passed a bill that seemingly guaranteed virtually unlimited funds for an accelerated magnetic fusion development program. In the few years since, the support for such an approach has disappeared and now the program is even considering abandoning the technological approach all agree has the best chance of producing a burning plasma soonest, in favor of riskier approaches that may have less expensive development steps. In view of the fact that the perception of what is affordable can change so quickly, some advocate waiting until the climate changes back, confident in their expectation that the present glut of energy will fade and that the national resolve will return to development of fusion power. This may happen, of course, but it would seem somewhat foolish to plan on it. When the glut fades, as it surely will, many factors will determine the national response to it. Energy conservation technology is now a dynamic force in many sectors of our economy. Nuclear fission makes up a larger fraction of our energy supply. Our foreign oil imports are not as large. The strategic petroleum reserve is a reality. Because of these differences and of political uncertainties, it seems wiser to plan a fusion development path that is flexible and able to take advantage of opportunities as they arise.

One of the reasons that magnetic fusion development facilities cost so much is that there is a natural minimum size for a self-sustaining fusion plasma; it becomes progressively more difficult to make smaller devices work. The same situation exists in inertial fusion. The smaller the fuel capsule, the more difficult it is to compress it to the proper

*Work performed under the auspices of the U.S. DOE by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-38.

conditions for high-gain performance. Our current estimate is that to obtain high gain will require a driver with 5 to 10 MJ, very complex pulses. We believe the technology to build such a driver exists today; the only difficulty is cost. Scaling up from current Nova technology suggests a driver cost of a few billion dollars and no one currently perceives that as affordable. We have, therefore, embarked on an intensive effort to bring the driver cost down; and we believe that significant progress has been made. It now appears that the laser driver necessary for high gain can be built for a few hundred million dollars.

While this price tag may put the ICF facility within reach (particularly if some external event increases national resolve), it would be prudent to continue looking for ways to make the facility seem more affordable. One way to do this is to make ICF development facilities attractive to more than one user group, i.e., make them multipurpose facilities. Since ICF technology has many present and future applications, it is in a good position to adopt this strategy. In this paper, I will outline the various possible applications of ICF technology, sketch development paths for each, and examine the implications on design and operation of the ICF development facilities if multipurpose use is allowed.

ICF APPLICATIONS AND THEIR DEVELOPMENT REQUIREMENTS

ICF technology can be used for both military and civilian applications. The military applications include study of nuclear weapon physics, vulnerability and lethality studies, and production of Special Nuclear Materials (SNM) for weapons. Some civilian applications are: (1) use of X-ray lasers as a diagnostic tool, (2) fissile fuel production, (3) electric power production, and (4) space propulsion. Naturally, the details of the military applications of ICF technology are classified. However, enough of the general principles can be stated that facility requirements can be laid out in broad terms in an unclassified forum. Fusion power development will be used as the baseline with which to compare other applications.

Fusion Power

The ICF application that most present work is oriented toward is the production of electricity. We are all well aware of the advantages of fusion for this application and are working hard to reduce any limitations.

The development steps and facilities proposed by many people have similar characteristics (see Fig 1). On present ICF facilities researchers are studying driver technology, driver/target coupling and target implosion dynamics but they will not be able to achieve high gain. It is generally agreed that the next step is to build a facility capable of assuredly obtaining high gain ($G \geq 100$). In such a high-gain test facility (HGTIF), the physics of burning targets can be studied in detail and the dependence of target gain on driver energy can be fully resolved for a variety of target types. This facility needs a driver with greater energy and peak power capabilities than will ultimately be required for a reactor, and one that has a great deal of flexibility in pulse duration, pulse shape and wavelength. The facility need provide pulses only occasionally (a few per day) and need last only about 10^4 shots.

Fig. 1. Typical Commercialization scenario for an ICF power reactor

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The next development step is assumed to be an engineering test facility (ETF) in which several potential reaction chamber concepts can be tested so that the best wall protection and chamber clearing ideas can be identified. In one development scenario¹ this is assumed to be an add-on to the HGTF using the same driver. In this case, it would be desirable to have the capability to pulse the driver several times in a short burst even if the driver were not fully rep-rated for continuous operation. For example, perhaps a 10 MJ driver could also be capable of delivering 5 pulses, each at 2 MJ, in rapid succession (assuming that will have learned how to make a capsule burn with only 2 MJ after some target performance improvements). Alternatively, the ETF could be a new facility or added-on to a rep-rated driver developed independently of the HGTF. In any case, the ETF would be the first facility with multipulse capability but it need not maintain the pulse rate for long times. Driver requirements for the ETF are similar to those for the HGTF with the exception that bursts of several or a few tens of shots are desirable and the driver lifetime needs to be about an order of magnitude larger.

An experimental power reactor (EPR) would be the next facility needed. In this facility, the best rep-rated driver would be integrated with the most desirable reaction chamber concept for thorough engineering and systems testing. It's possible that the ETF could evolve into the EPR. Finally, a demonstration power reactor would be needed to provide the economic and reliability data base necessary for industry to make commercial construction decisions. These last two reactors require fully qualified drivers in terms of pulse rate but do not need the pulse flexibility of the HGTF and the ETF.

Nuclear Weapon Physics

When a nuclear weapon is exploding, very large energy densities are suddenly created in normal or super dense materials, resulting in dense, highly-ionized, high-temperature plasmas. As the materials move, instabilities at the interfaces become important. The equation of state and opacities of such materials are difficult to calculate and the conditions are not easy to reproduce in the laboratory, making measurements scarce. The materials may or may not be in local

thermodynamic equilibrium at any given time and it may be important to follow the dynamic processes in detail. These topics are studied in underground nuclear tests, of course, but these are expensive and few. The development of a good laboratory simulator would be of great value.

All that is required to bring this application to reality is a high peak power density over a large enough area to be interesting. The laser drivers needed for ICF research are themselves capable of doing this. The Novette laser was the first with enough power and flexibility to produce interesting conditions. Focusing a 450 ps pulse onto a thin selenium foil 200 μm wide by 1 cm long, Novette had a power density of $5 (10^{13}) \text{ W/cm}^2$ with 0.53 μm light. This produced a plasma with an electron density of $3 (10^{20}) \text{ cm}^{-3}$ and a temperature high enough to strip 24 electrons from each selenium atom. Obviously, with this capability the weapon physics experiments have already begun. With each increase in power density available, additional regimes of weapon physics become accessible. When high gain is obtained, not only will a factor of 100 in energy density be added, but there will also be the possibility of using the output of the fusion capsule to create unique conditions in matter.

While use of ICF facilities to study nuclear weapon physics will be of significant value, it will not replace nuclear tests or elaborate computer simulations. Since all physical phenomena do not scale in exactly the same way, ICF microexplosions would not be scaled replicas of nuclear weapons. The best ICF can do is to study some of the fundamental physics and to collect data that will help normalize models and test theories. The extrapolation to full size will always need complex numerical simulations and benchmark underground tests as it does today.

To do weapon physics experiments in ICF facilities will require little modification of the basic facility design. However, there are additional requirements for diagnostic capabilities, target irradiation geometry (e.g., cylindrical focusing) and expanded ranges for pulse length, pulse shape, and wavelength flexibility.

Vulnerability, Lethality, and Effects

When a nuclear weapon explodes, its energy is emitted in the form of neutrons, X rays, γ rays, and debris. These forms of energy interact with the environment and with other military systems. The study of these interactions is referred to as vulnerability, lethality, and effects (VLE) work. The military system designer must determine the vulnerability of his system to the effects of an opponent's warhead and he must determine the lethality of his own warheads when used against the opponent's systems.

The number of possible physical interactions between an exploding nuclear warhead, the environment, and another military system is very large. The VLE community has spent considerable effort identifying the dominant interactions for any given engagement scenario. The list is too long to reproduce completely here, but a few examples of relevance to ICF are discussed. The weapon output may interact directly with the opposing military system, or it may interact with the environment first, creating a different effect that the system designer must account for (such as blast or electromagnetic pulse [EMP]). Neutrons cause fissions in an opponent's warhead that can lead to undesirable heating. X rays can create shock impulse in the skin of a reentry vehicle. X rays and γ rays can cause photo or Compton electrons to be emitted from the circuit elements inside a system. The rebounding electrons can create

large pulses of electromagnetic energy in those same circuits. Radiation of various sorts can cause loss of bits of information in integrated circuits.

To study these effects, the VLE community has built many laboratory simulators and has done large underground effects tests using nuclear explosive sources. To be realistic the simulation must recreate the energy partition, output spectra, time scale, environmental effects, and interactions between all phenomena. There are a large number of possible output characteristics of nuclear devices and a large number of engagement scenarios. Not surprisingly, the present simulation methods are not adequate to cover all the cases of interest. Even underground nuclear testing does not have complete fidelity (try simulating a space engagement underground).

ICF technology can be used to significantly increase this country's VLE understanding. However, the existing simulators already do a better job than what can be done with any existing ICF driver alone (except for studying system vulnerability to lasers themselves, of course). Even small thermonuclear yield (gain 1 to 10) won't exceed current capability except in very limited cases. It will require thermonuclear yields of more than a few hundred megajoules to make ICF attractive to this community. For many effects the entire structure (or circuit) must be present in its real geometry to create the effect. Only at large ICF yields do we reach this capability.

To exploit ICF's capability, once high gain is obtained, there must be space to expose large pieces of hardware (Fig. 2). The VLE community is interested in a variety of output spectra and energy partitions, and we should anticipate the need to alter the output of the fusion capsules we design. In general our explosion time scales are much shorter than those of interest and here again we will be asked to alter the effect time scale to the extent possible. It's also likely that the target chamber will be required to handle fissionable material.

X-ray Laser Applications

The peak output brightness obtained in the X-ray laser experiments to date is $6 (10^{10}) \text{ W/cm}^2\text{Åsr}$. These small X-ray sources have a brightness that is 10^{10} times greater than today's most powerful X-ray generators and synchrotron sources. They are, of course, presently one-shot, short-pulse devices that need a great deal more effort before they become useful laboratory X-ray sources. However, the potential exists to make this a very useful tool. Many possible applications have been suggested; I will use just one as an illustration.

It has been proposed to do X-ray holography on biological organisms. The spacial resolution would be comparable to that from an electron microscope (50-2000 Å), but with X rays the exposure could be done for living tissue, ending the speculation about whether the sample preparation alters the structure of the tissue being examined. Some experiments that have been suggested include studies of the cell membrane structure, nerve fiber interconnections, and the morphological differences between normal and malignant cells.

Some simple (non-holographic) experiments could be done with the present x-ray laser capability. However, more will become accessible as the driver power increases and the wavelength of the X rays shortens. The high brightness source mentioned above is at a wavelength of about 200 Å. Some lasing was detected at a wavelength of about 150 Å in

Fig. 2. The target chamber used for vulnerability, lethality, and effects (VLE) experiments will have to allow for substantial exposure areas and distances.

yttrium. To do the microholography we would need a bright source at perhaps 30 Å. Cylindrical focusing and very short pulses (sub-nanosecond) are, of course, very important for this application.

Production of Nuclear Materials

The neutrons in a fusion reactor can be used to produce valuable nuclear materials. This is now done in fission reactors to produce plutonium and tritium for our nuclear weapons stockpile. Fusion has a natural advantage over fission for this application because the neutrons have the potential of being cheaper. The cost of a reactor is strongly dependent on its thermal power. A fusion reactor has many more excess neutrons available per unit thermal power than a fission reactor. The advantage is a factor of nine or ten compared to a fission reactor that obtains fuel from another source and a factor of 30 to 60 compared to a breeder reactor. In one design using a Be neutron multiplier and flowing Li to produce tritium, a tritium breeding ratio of 2.1 was calculated with a thermal power of 530 MW. This design could produce excess tritium (beyond that needed to fuel itself) at a cost a factor of two or three lower than that from a new fission reactor. Such a reactor could produce tritium and plutonium for the military and/or ^{235}U for fission reactor fuel.

Materials production will only come to economic fruition when a pulse rate over 1 Hz becomes available in addition to high gain. To develop this application will require a full-scale, engineering-development program. It is possible to do some integrated neutronics tests and some chamber phenomenology experiments on the HGTF. The nature of these first

experiments would be similar to those for power reactor development but would use different materials. Production testing might be begun on the ETF, necessitating the availability of more extensive radioactive materials processing capabilities than are necessary for power reactor development alone.

Space Propulsion

In this application fusion capsules are ejected into a thrust chamber at the rear of a space vehicle and burned at the rate of tens or even hundreds of pulses per second. Magnetic fields are used to divert the debris and produce thrust in the desired direction. While the propulsion system for such a vehicle is very large (perhaps 500 tons), it has rather unique properties. Specific impulses of 10^5 s or more are achievable along with specific powers of 100 W/g. With such a rocket, payloads of 1500 tons could be moved between earth and mars in 43 days and between earth and some nearby stars in a few tens of years.

The development path for such a capability is very long. Most proposals use advanced fuels like D-³He or D-D in order to increase the debris yield relative to the neutron yield. However, some thought is being given to seeing how good a rocket can be made with D-T fuel for a nearer future scenario. If such a system appears to be attractive, then there may be some development steps that could be taken on the next few ICF development facilities. Obviously it would be desirable on the HGTf to test D-T targets in which the amount of debris yield is maximized. Different methods of converting the capsule yield to thrust could also be tried on both the HGTf and the ETF. Considerable driver flexibility would be desirable for these different and less well-defined targets.

THE IMPACT ON ICF OF SHARING FACILITIES

Each new ICF development will create a capability that can be used by one or more of the applications. Whether it is so used or not will depend on whether the ICF facility is designed to be flexible enough to take advantage of the capability in a way acceptable to those interested in the application. This will require careful planning on the part of the ICF community. First, let us consider, in Fig. 3, the time ordering of the applications relative to the ICF development steps. In present facilities, ICF physics, weapon physics, and X-ray laser experiments coexist. High gain would expand the demand in these areas and add an interest in VLE experiments. When a rep-rated driver is developed, it would then make materials production and commercial power applications available. Finally, if advanced fuels or targets become available, then space propulsion becomes an interesting application.

While each application cannot be brought to complete fruition until the ICF development shown in Fig. 3 is realized, the development paths for each of the other applications contain some elements that can be done on earlier ICF research facilities. If the prospect is good for ultimate realization of the full ICF capability, there would, no doubt, be considerable impetus for these earlier experiments. Achievement of high gain in the laboratory will be taken by many as the signal to take ICF seriously. Thus, the HGTf, the ETF, and perhaps the EPR should probably be capable of doing some experiments for all the applications discussed. The design and operation of these facilities would be impacted in a major way by their contemplated multipurpose use. On the other hand, at some point (e.g., a demonstration power reactor) the facility would be so specifically designed for a particular application that the usefulness to others would be limited.

Fig. 3. Important applications of ICF technology in the Laboratory are available at each development step.

In Fig. 4 the ICF development facility steps are repeated with the experiments that can be done for other applications superimposed. Thus, besides doing ICF high-gain experiments, the HGTF could do expanded weapon physics and X-ray laser applications experiments, VLE exposure and phenomenology tests, first wall exposure tests for both material and power reactors, and target design and the first thrust-concept experiments for propulsion. The first thing to notice is that if all these activities were to be done in series, work on the machine would probably last for a very long time but there would be a big fight about priority. It is clear that to accommodate so many applications, the HGTF should have multiple target chambers as shown schematically in Fig. 5.

The use of multiple target chambers is not new. Nova (and reportedly Gekko) are currently supporting more than one chamber. In the Nova arrangement either ten beams are sent to the main chamber or two beams are sent to a different chamber. Experiments in the different chambers are not done at the same instant but on successive pulses (which, on Nova may be hours apart).

Several advantages accrue from the use of multiple chambers. The major time consumption for an experiment is the set-up and take-down in or near the target chamber. Often the changes necessary in the laser configuration can be accomplished much faster. The set-up and take-down often involves different groups of people for the different applications (and perhaps even for different experiments for a given application). Thus, these people can be working in parallel, in separate areas, and several types of experiments can be handled during each driver campaign. Each application is able to do its work on its own time schedule. Since the target chambers are inexpensive relative to the laser, and the costs of the driver construction and operations are shared, total costs for each application are more affordable. Some of the applications require large areas that can be exposed to high fluxes from the targets. Others may use materials that will contaminate a target chamber requiring considerable clean-up time. Using separate chambers mitigates the impact of these problems. If the chambers can be isolated from one another

Fig. 4. Applications of ICF technology other than power production that could do experiments on multipurpose ICF development facilities.

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Fig. 5. The use of multiple target chambers will facilitate experiments for many applications on ICF development facilities like the HGTF and the ETF.

adequately, it is even possible that classified and unclassified applications could share the same driver but exist in separate experiment buildings. This suggests that there, at least, be chambers for basic ICF studies, military applications, and perhaps industrial applications. Priorities could be sorted more easily because delays would be minimal for the different groups (determined by beam switching and pulse alteration times). If adequate space is allowed and the driver characteristics are flexible enough, the chambers could be built sequentially, as the need arose.

Including the capability to support multiple chambers has some implications on the appropriateness of ICF technologies under consideration. Laser and heavy-ion drivers of some types would be able to support multiple chambers with no difficulty. However, light ion, free electron laser, and compact torus drivers would have considerably more difficulty, if it is possible for them at all. In addition, it is clear that supporting multiple chambers would be considerably easier using indirect drive targets than in using direct drive ones. However, the issue of target classification would have to be addressed if one of the experimental areas was to be unclassified.

The second major issue in multiple use of ICF development facilities is the flexibility of the driver to provide pulses appropriate to all applications. Table 1 contains a comparison between the driver requirements for power reactors and those for the HGTF, assuming that multiple applications are contemplated. It is clear that the HGTF driver would have to be considerably more flexible than the reactor driver, but would not have to be capable of high-average power. While it would be better if the same technology could be used for both the research and the reactor drivers, it is not necessary. While the HGTF is being built and operating, it is likely that much further research will be done on high-average-power drivers for various applications (including power production and SDI). It would be a mistake to delay the HGTF until all the preliminary research on these alternate high-average power drivers is done to make a choice for the HGTF. It is sufficient that a possible development path to a reactor driver is foreseen for the chosen HGTF driver. It is more important to emphasize performance parameters that can assure high gain and provide the flexibility necessary to support multiple applications.

A final impact of a multipurpose-facility, development scenario for ICF is the effect on support facilities. These would have to be expanded, also. The target fabrication facility would have to make a variety of target types. Diagnostics support would have to be broader, although some of the diagnostics for each application could be brought in by the interested group. Data collection would probably be done separately for each experimental area with only laser pulse characteristics collected in common and piped to the appropriate area. While these expanded capabilities would seem to raise the operating costs of such a facility, the operating costs could be cut for each application by sharing the laser operating personnel and many target fabrication and diagnostics personnel. The impact on the ETF would be similar to the that for HGTF. Multiple chambers, driver flexibility and shared support facilities would still be important. It is likely, though, that by the time an EPR is built, driver flexibility will be a lower priority. It will be important to choose the driver that is best for the primary mission of the facility and let the other applications take what they get or build their own facility. Another important addition that a multipurpose ETF would require is an expanded chemical processing capability that could handle all the types of materials anticipated for the various applications.

Table 1. Driver requirements for research and development facilities like the high-gain test facility (HGTf) and the engineering test facility (ETF) emphasize flexibility and broad parameter ranges whereas those for a commercial reactor can be less flexible but need high average power and high durability and reliability.

	<u>Research Driver</u>	<u>Reactor Driver</u>
Pulse energy	5-10 MJ	3-5 MJ
Peak power	500-1500 TW	~ 500 TW
Pulse duration	0.1-100 ns	5-10 ns
Pulse shape	Flexible	Fixed, complex
Pulse rate	Few per day	5-10 Hz
Efficiency	Little importance	≥10%
Wavelength	Flexible, 250-1000 nm	Fixed, ~ 500 nm
Focusability	Flexible geometry	Fixed, 1 mm spot at several meters
Reliability	?	>70% availability
Durability	10 ³ -10 ⁴ shot life	~10 ¹⁰ shot life
Maintainability	Skilled, controlled	Routine, hands on
Cost	25-50\$/J	100-150\$/J

CONCLUSIONS

It would appear that a possible development scenario for ICF would include the building of facilities that could accommodate a number of applications, in addition to doing the search necessary to further the basic ICF goals. Indeed, in view of the fact that ICF already has multiple goals, both military and civilian, it is clear that this development scenario will occur. The only question is the number of such applications that will be accommodated.

Proceeding along such a development path has advantages for ICF in that there can be a number of constituencies that have an interest in seeing ICF make progress. Each one may perceive the cost of the next step as affordable if it can be made clear what his share of the total is. It may be that such a development strategy will provide a more stable support level by being less sensitive to the changes in national priorities (although it will be as sensitive as any other strategy to across-the-board cuts). It should be recognized that there are also risks to such a strategy. During times of general budget squeeze, each constituency may cut back more than his share in the hope that the others will have to take up the slack. It is also possible with many constituencies to spread effort so thin that good work is not done on any application.

In order to successfully carry out such a development strategy for ICF, careful planning is required. Before each new facility is approved, the needs of all the constituencies will have to be considered. This has not always been done in the past and there has already been some awkwardness. It is clear that driver flexibility, use of multiple chambers, and shared support facilities must be included in the planning for the high-gain test facility and the engineering test facility. If

this planning is done properly there is good reason to believe that the multipurpose development facility strategy can be done successfully and that ICF will be developed more quickly as a result.

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