

5.5 Research and Development Assessment

An important part of a conceptual reactor design study such as Prometheus is the identification of important research and development needs to resolve the key issues. An R&D assessment has been carried out for Prometheus to serve three purposes: (1) provide programmatic-decision makers with a list of important R&D tasks that need to be carried out, (2) provide part of the input for a comparison study between the Heavy-Ion and Laser-driven reactors, and (3) identify areas of R&D that are common to inertial and magnetic fusion energy.

This assessment has not attempted to develop a comprehensive R&D plan for IFE. Developing such a plan requires detailed analysis of experimental facilities and careful consideration of the time sequence and cost of such facilities in order to minimize the overall R&D cost and time and maximize benefits. Rather, this effort has focused on identifying the R&D required to resolve the critical and key issues described earlier in this chapter.

A specific development goal was selected as the ultimate objective of the R&D items described here. This goal is to develop the physics and engineering data base sufficient to construct an IFE Experimental Power Reactor (IEPR). It is difficult at this stage of IFE research to specify the detailed characteristics of an IEPR. However, IEPR is envisioned as a facility in which the basic physics and engineering performance as well as system integration tests are carried out. IEPR scope and mission similar in many respects to ITER in the magnetic fusion energy program as they both provide the data base necessary to construct a Demonstration Power Plant (DEMO). IEPR will have prototypical components and will probably produce several hundred megawatts of fusion power and operate with about one pulse per second and overall availability of 20-30%.

The R&D assessment here focused primarily on critical components unique to IFE: target, driver, and cavity. Some modest R&D has also been identified for the tritium systems and safety. Because a number of key issues can be resolved through experiments on the same facilities, the R&D presented below has been organized so that each R&D item relates to one key issue or a group of issues. In this latter case, the issues involved are clearly indicated using the numbering system used earlier in the Key Issue Summary Table. A summary of R&D costs for the laser reactor option and heavy ion option is included in Section 7.3.6 in the comparison chapter.

5.5.1 Research and Development Requirements for Targets and Drivers

The majority of the most urgent Research and Development (R&D) requirements for IFE Targets and the two types of drivers are inextricably linked together. Some of the most difficult issues having exclusively to do with the drivers involve the demonstration of the generation and delivery of high energy pulses; these same high energy pulses from the driver are requirements for solving significant issues associated with target design and development.

Target/Driver R&D - IFE target irradiation requirements basically define the driver designs. If faulty target design gives rise to unnecessary or inappropriate driver requirements, expensive and unnecessary driver development may occur without advancing the state of the art. Furthermore, experimental evidence and theoretical simulations have shown that the IFE target implosion physics is strongly dependent upon the scale of the target, so that data derived from small (kJ scale) driver/target interaction experiments cannot be easily extrapolated to aid in the design or predict accurately the performance of reactor-sized targets (requiring irradiation energies of the order of MJ).

Thus, in order to design an optimum reactor-sized DT target, a strong, long-term IFE R&D program involving experiments and analyses associated both with drivers and targets must be established. This would permit the development of a series of DT target designs of increasing scale, beginning at our present stage of understanding, and proceeding in an orderly manner to IFE target ignition and beyond, with the desired optimum reactor targets having yields of the order of hundreds of MJ.

This orderly series of target/driver interaction experiments is crucial to the success of an IFE reactor development program because there are a variety of competing processes to efficient thermonuclear "burns" of the DT fuel which have unique scale lengths. These competing processes can lead to anisotropies in target compression, preheating of the cryogenic DT fuel, generation of plasma instabilities, etc. As target dimensions increase, many of the strengths of these competing processes can grow exponentially. Frequently, variations of one or more parameters in target or driver design can check the growth or otherwise control an undesirable competing process, thereby permitting continued progress toward achieving ignition, thermonuclear break-even, and eventual demonstration of optimized target/driver designs for cost-effective IFE reactor operation.

In the case of the HI driver, a crucial series of driver/target experiments conducted with indirect-drive HI DT targets would be to demonstrate that heavy ion beams converted at each end of an HI indirect-drive target efficiently produce soft X-rays in an energy range suitable for achieving the Rayleigh-Taylor irradiation requirements for a uniform implosion of the DT target within the hohlraum. This could prove to be one of the chief

advantages for the HI IFE driver over a comparable UV excimer laser driver. Verification of the accuracy of this prediction is a crucial step in allowing future IFE reactor designers to make appropriate choices as our database for both targets and drivers is enlarged by implementation of a well thought out IFE R&D plan.

Although some laser/target irradiation experiments could be conducted using subscale beams associated with parallel driver development efforts, a key demonstration for the success of the Prometheus-L laser driver interacting with direct-drive targets is the uniform ~1% target illumination with 60 beams, totaling 4 MJ. Another important series of key, full-scale R&D experiments involving both direct-drive targets and laser drivers would be the demonstration that the long laser prepulse doesn't significantly contribute to target preheat by generating hot electrons and hard X-rays via stimulated Brillouin and Raman scattering in the plasma atmosphere blown off from the target by the long duration prepulse.

Target R&D - Once the riddles of IFE target design are being solved by implementation of an aggressive plan exploiting extensive driver/target R&D experiments and analyses, there are a series of purely target-related requirements which need to be explored in parallel with the other programs. Development of cost-effective, target fabrication methods leading to economical mass production for IFE reactors needs to be carried out. R&D for innovative methods of accurately placing IFE targets at the centers of target chambers at around a 5-Hz rate is of crucial importance. There may be significant target/driver alignment advantages associated with having IFE DT targets injected into reactor target chambers with zero net velocity following injection and, hence, target injection R&D might deal with developing techniques which may permit this goal to be achieved.

Some modifications to target designs may be required in order to enhance the alignment of the DT targets relative to the driver beams. An example might be the addition of a "shine shield" on a direct-drive laser DT target so that aligning laser beams may be used to sense the position of a DT target with a high degree of accuracy.

Driver R&D - Although a series of parallel subscale R&D experiments, analyses, and technological innovations must be carried out for the IFE HI driver, the vast majority of meaningful HI driver R&D developments must be conducted at or near full scale; i. e., at energy levels of the order of MJ with pulse durations of the order of 10 ns. In particular, our understanding of the physics of heavy ion (HI) drivers will not significantly benefit from HI experiments conducted with pulsed energies of the order of only a few tens of kilojoules because these sub-scale experiments do not overlap the HI driver parameter space occupied by candidate HI IFE reactor drivers.

The Prometheus-H heavy ion (HI) driver design calls for the delivery of 7.8 MJ in 18 beamlines, of which 12 are bunched into ~7 ns pulses and the remaining 6 beamlets are bunched into ~30 ns pulses. This corresponds to approximately 420 kJ/beamline. Transport experiments with a single, space-charge limited HI beam may be useful, but a key HI driver demonstration goal will be the successive achievements at full scale energy (~4 MJ) of ballistic focusing, stripping, channel formation, and stable, self-pinch transport to the target. However, as noted above, the same HI facility that can demonstrate these fundamental capabilities for the driver can also be used to test HI target design parameters.

In an analogous manner, off-line HI development programs can be established to develop low emittance, doubly-ionized heavy ion (Pb^{+2}) beam sources, cost-effective superconducting dipoles, expert control systems, channel formation techniques, HI beam alignment systems, etc. R&D programs associated with achieving significant reductions in Metglas losses could be carried out in parallel with other R&D efforts designed to optimize the single beam LINAC operated in a burst mode. Construction of a series of full-scale HI storage rings suitable for demonstrating that a single beam LINAC operated in the burst mode can deliver an adequate number of comparable low emittance beamlets suitable for ballistic focusing into a pre-formed channel.

Although a series of parallel subscale R&D experiments can be conducted for the laser driver, again the vast majority of meaningful R&D developments must be conducted at or near full scale; i. e., at energy levels of the order of MJ with pulse durations of the order of 10 ns. Similarly, there are a number of IFE laser driver issues which require operation of a least one beam line at full scale energy. In the case of the Prometheus-L KrF laser design, this would be an ultraviolet (UV) laser beam of energy ~80 kJ generated from a combination of using a large number (16 to 25) moderate energy (4 to 6 kJ) electric-discharge excimer lasers to pump a large aperture (1.2 m) Raman accumulator cell which, in turn, pumps a backward stimulated Brillouin scattering (SBS) pulse compression cell yielding a pulse duration of approximately 6 ns with a wavelength of ~250 nm.

As described below, the Prometheus-L KrF laser driver requires extensive development of workhorse excimer laser amplifiers, reliably producing output energies ranging from 4 to 6 kJ with moderately good beam quality. An ambitious goal for these laser amplifiers is to have them reach a level of $\sim 10^9$ shots between failures.

Again, however, it should be emphasized that the natural consequences of solving these driver component development problems in parallel following an orderly plan is the step-by-step construction of a driver facility suitable for performing full scale target irradiation experiments.

5.5.2 Target R&D

Many of the issues and associated R&D for the target are closely related to those of the driver. In this subsection, the R&D most closely related to the target is discussed. In the next subsection, the required R&D for the driver is presented together with the cost estimate for both the driver and target R&D.

5.5.2.1 Direct Drive Target Coupling (Key Issue A.a.1)

Description - Areas requiring R&D for this issue include:

- Proof of ability to model plasma physics correctly - Experiments with high gain targets to establish agreement with computer models.
- Studies of development of hydrodynamic instabilities and target break up/mixing for reactor size targets - Experiments to show that growth of Rayleigh-Taylor and other instabilities agrees with reactor-size targets and that symmetric implosions can be achieved.
- Illumination symmetry and laser light absorption for reactor size targets - Experiments to demonstrate sufficiently smooth beam profiles with correct apodization and laser light absorption in a agreement with computer models.
- Accurate pulse shaping - Experiments to show that pulses can be shaped with sufficient accuracy to implode targets on a low adiabat and, at the same time, generate converging shocks sufficient to ignite a small, central hot spot (spark plug).

Facility - Direct drive experimental facility: Such a facility would be especially useful should the ignition and gain facility be capable of illuminating indirect drive targets only, but should probably be built in any case. It should be capable of delivering 100 to 500 kJ on target from 60+ beams. It would be used to demonstrate ignition of direct drive targets.

Cost and Time - These will depend on when and how the facility described above is built. Most economical path will probably be a direct drive experimental facility constructed as an upgrade of the OMEGA laser system at the University of Rochester. Cost estimates are given in the next section on the Driver.

5.5.2.2 Survivability of Targets in Chamber Environment (Key Issue A.a.3)

Description - Areas requiring R&D for this issue include:

- Hydrodynamics of target/cavity interaction. Once this environment is known, theoretical studies using modern hydrodynamics and heat transfer algorithms should be able to settle the question of target survivability. Experimental work would be useful to check code results, but should be limited in scope and capable of being carried out in existing facilities.

Facility - It will probably be unnecessary to build a separate facility to address this R&D issue.

Cost and Time - Once the cavity environment has been specified, it will not be expensive to address this issue in either cost or time. A theoretical study coupled with limited experimental research could be conducted at a national laboratory or university. It should be possible to complete the R&D within two or three years.

5.5.2.3 Demonstration of Injection and Tracking of Targets Coupled with Beam Steering (Key Issue A.b.1)

Description - Areas requiring R&D for this issue include:

- Target injection and tracking/beam steering - Experiments to show that targets can be injected reliably and tracked with sufficient precision.
- Illumination symmetry and laser light absorption for reactor size targets - Experiments to demonstrate sufficiently smooth beam profiles with correct apodization and laser light absorption in agreement with computer models.

Facility - The technology required here has not been demonstrated in IFE or any other field. A separate facility should probably be built.

- Target injection/beam steering simulator. This facility will be used to prove that accurate illumination can be achieved in a reactor scenario. Full size steering components will be used, but actual beams need only be sufficiently intense to provide accurate diagnostics. The facility will include a full scale injection system capable of repetition rates of around 10 hertz.

Cost and Time - This facility might be built at Sandia or Los Alamos at a cost of \$100-300 million. Annual operating cost would be around \$20 million. The facility would take about three years to build. The R&D program would last about five years.

5.5.2.4 Manufacturability of High Quality, Low Cost DD and ID Targets (Key Issue A.c.1)

Description - R&D in this area will establish the ability to mass produce targets at low cost using already demonstrated technologies. Considerable advances have been made in the fabrication of individual targets using microencapsulation, microfabrication, droplet generators, etc. Research in this area will establish whether any of these demonstrated techniques are viable for mass production, and identify alternative methods. To date, no major research effort has been devoted to mass production of IFE targets. The R&D effort in this area would include experimental and theoretical work. Funding should be on a level sufficient to attract significant attention

to the problem. It is likely that numerous existing chemical and industrial processes could be profitably applied to mass produce targets. It is a question of making the best talent aware that the problem exists.

Facility - It will probably be unnecessary to fund major new facilities for this R&D. Once the best processes have been identified, existing facilities at major industrial companies or universities will probably be capable of proving the potential for mass production.

Cost and Time - Although new facilities are probably not needed in this area, significant amounts of time and money will be required to attract the necessary research in the area. Expenditures of \$200 million over 10 years would not be unreasonable.

5.5.2.5 Overall R&D - Significant technical R&D will be required in areas of target physics, production, and operation which is not necessarily covered in any of the key issues. Therefore, the following is included as a catch-all for what the key issues for the target area have missed.

Description - Overall R&D covers some of the areas already identified above as well as areas not specifically identified among the target key issues, and the scope of the required R&D is accordingly large. We have tried to cover below all areas which we feel require a significant R&D effort within the target physics and engineering-related areas.

- Target implosion on a low adiabat - Experiments to demonstrate efficient compression without excessive preheat before ignition.
- Test of target designs - Experiments to prove that high gain can be achieved with proposed target designs.
- Proof of ability to model plasma physics correctly - Experiments with high gain targets to establish agreement with computer models.
- Central spark ignition and propagating burn - Experiments to prove that bootstrap heating by fast alpha particles can generate an outward-propagating burn wave leading to efficient thermonuclear burn.
- Studies of development of hydrodynamic instabilities and target break up/mixing for reactor size targets - Experiments to show that growth of Rayleigh Taylor and other instabilities agrees with predictions for reactor-size targets, and that symmetric implosions can be achieved.
- Significant gain for low mass targets - Experiments to prove that economically attractive gain can be achieved with 1-10 MJ drivers.
- Hohlraum physics - Experiments to show agreement with predictions of computer models.

- Non-LTE radiative transfer. Demonstrate agreement of code-predicted radiative transfer with experiments for reactor-size indirect drive targets.
- Target injection and tracking/beam steering - Experiments to show that targets can be injected reliably and tracked with sufficient precision.
- Illumination symmetry and laser light absorption for reactor size targets - Experiments to demonstrate sufficiently smooth beam profiles with correct apodization and laser light absorption in agreement with computer models.
- Accurate pulse shaping - Experiments to show that pulses can be shaped with sufficient accuracy to implode targets on a low adiabat and, at the same time, generate shocks sufficient to ignite a small, central hot spot (spark plug).

Facility - It will probably be necessary to build several facilities to conduct the experimental programs outlined above. These might include:

- Ignition and gain facility: This facility should be capable of delivering at least one megajoule of beam energy. It should have at least 32 beams and an independent backlighting system.
- Target injection/beam steering simulator: This facility will be used to prove that accurate illumination can be achieved in a reactor scenario. Full size optics will be used, but beams need only be sufficiently intense to provide accurate diagnostics. The facility will include a full scale injection system capable of repetition rates of around 10 Hertz.
- Direct drive experimental facility: Such a facility would be especially useful should the ignition and gain facility be capable of illuminating indirect drive targets only, but should probably be built in any case. It should be capable of delivering 100 to 500 kJ on target from 60+ beams. It would be used to demonstrate ignition of direct drive targets.
- Demonstration reactor: This facility will demonstrate IFE production at the 10 to 100 MWe level.

5.5.3 Driver R&D

5.5.3.1 Summary of R&D Tasks for Target and Driver Key Issues - There are a wide variety of research and development (R&D) efforts which need to be carried out to assist with the development of viable target and driver designs.

R&D work relevant to specific key issues associated with the Prometheus laser driver described here include:

- A.a.1 Direct Drive Target Coupling,
- A.a.2 Indirect Drive Target Coupling,
- A.a.3 Survivability of Targets in Target Chamber Environment,
- A.b.1 Demonstrating of Injection and Tracking of Targets Coupled with Beam Steering,

- A.c.1 Manufacturability of High Quality, Low Cost Direct-Drive and Indirect-Drive Targets,
- B.a.1 DT Target Illumination Issues,
- B.a.2 Large Laser Development and Bandwidth Issues,
- B.a.3 Final Optics Pointing System,
- B.a.4 Grazing Incidence Mirror Damage,
- B.a.5 SBS Pulse Compressor,

Recommended R&D work associated with the Prometheus-H heavy ion driver include the following relevant key issues:

- B.b.1 Timing of Heavy Ion Beams,
- B.b.2 Heavy Ion Channel Formation,
- B.b.3 Heavy Ion Channel Transport,
- B.b.4 Stripping of Heavy Ion Beam,
- B.b.5 Alignment of Indirect Heavy Ion Target

Summary of R&D Cost Estimates

Table 5.5-1. Summary of Laser Driver R&D Task and Duration Estimates

<u>No.</u>	<u>Task Description</u>	<u>Estimated</u>	<u>Key Issue</u>	<u>R&D</u>
		<u>Cost</u>		<u>Duration</u>
1	Demo DD Target Beam Nesting	10 M\$	B.a.1	3 years
2	Satisfy Bandwidth Requirements	10 M\$	B.a.2	3 years
3	Laser Beam/Target Alignment System	12 M\$	A.b.1,B.a.3	4 years
4	Demo DD MJ DT Target Ignition*	400 M\$	A.a.1,B.a.1	10 years
5	Final optics pointing demo	5 M\$	A.b.1,B.a.3	3 years
6	Optics Damage Resistance Demo	5 M\$	B.a.4	3 years
7	Develop Robust GIMM	5 M\$	B.a.4	4 years
8	Develop excimer laser modules	20 M\$	B.a.2	3 years
9	Test to demonstrate 10 ⁹ lifetime	40 M\$	B.a.2	5 years
10	Demonstrate single 6 kJ beam line	80 M\$	B.a.2	4 years
11	Demonstrate 6x16=96 KJ beam line	120 M\$	B.a.2	2 years
12	Develop/Demo Laser Control System	40 M\$	B.a.2	5 years
13	Develop 50 J Raman seed generators	2 M\$	B.a.2	1 year
14	Demonstrate 6 kJ Raman converter	1 M\$	B.a.2	1 year
15	Demo 100 kJ Raman converter	20 M\$	B.a.2	2 years
16	Develop programmable SBS chirper	2 M\$	B.a.5	1 year
17	Subscale SBS PC demonstration	2 M\$	B.a.5	1 year
18	Develop Large Aperture SBS chirper	10 M\$	B.a.5	3 years
19	Demo 6 kJ SBS Pulse Compressor	5 M\$	B.a.5	2 years
20	Demonstrate 100 kJ Pulse Compressor	20M\$	B.a.5	5 years
Total Laser Driver R&D Costs		829M\$		

*Includes cost of Nova Upgrade.

DD = direct drive, GIMM = grazing incidence metal mirror, SBS = stimulated Brillouin Scattering, PC = pulse compression, DT = deuterium/tritium

Table 5.5-2 Summary of Heavy Ion Driver R&D Task and Duration Estimates

<u>No.</u>	<u>Task Description</u>	<u>Estimated</u>	<u>Key Issue</u>	<u>R&D</u>
		<u>Cost</u>		<u>Duration</u>
1	Demo Single Accel. in Burst Mode	15 M\$	B.b.1	3 years
2	Develop Brighter Pb ⁺² Source	10 M\$	B.b.1	3 years
3	Develop high brightness HI injector	20 M\$	B.b.1	2 years
4	Demo low emittance through injector	10 M\$	B.b.1	2 years
5	SP HI Pulse Synch. & Timing Demo	10 M\$	B.b.1	3 years
6	SP Triplet Focusing Demo	10 M\$	B.b.2	2 years
7	SP HI Channel Formation Demo	100 M\$	B.b.2	7 years
8	SP Injection of HI Beam in Channel	10 M\$	B.b.3	3 years
9	SP Demo of Channel Transport @ MA	50 M\$	B.b.3	5 years
10	SP HI Beam Stripping	20 M\$	B.b.4	2 years
11	SP HI Neutralization	5 M\$	B.b.4	1 year
12	Develop high PRF burst-mode pwr.sup.	30 M\$	B.b.3	2 years
13	Demo superconducting quadrupoles	20 M\$	B.b.3	3 years
14	Demo storage ring performance	50 M\$	B.b.3	3 years
15	Demo bunchers	25 M\$	B.b.3	3 years
16	Develop HID Computer Control System	20 M\$	B.b.5	5 years
17	Alignment of HI Beam to ID Target	400 M\$	B.b.5	10 years
Total Heavy Ion R&D Costs		805M\$		

SP = single pulse, HI = heavy ion, MA = mega-ampere currents,
PRF = pulse repetition frequency, HID = heavy ion driver, ID = indirect drive

Table 5.5-3 Summary of Target R&D Task and Duration Estimates

<u>No.</u>	<u>Task Description</u>	<u>Estimated</u>	<u>Key Issue</u>	<u>R&D</u>
		<u>Cost</u>		<u>Duration</u>
1	Demo Target Survivability in TC	5 M\$	A.a.3	2 years
2	Demo Target Injection/Tracking	10 M\$	A.b.1,B.a.3	3 years
3	Target Manufacturability Demo	10 M\$	A.c.1	2 years
4	Direct Drive Target Experiments (with >1 MJ Laser Driver)	200 M\$	A.a.1,A.a.3 A.b.1,A.c.1 B.a.1,B.a.2 B.a.3	5 years
5	Indirect Drive Target Experiments (with >1 MJ Heavy Ion Driver)	200 M\$	A.a.3,A.b.1 A.c.1,B.b.5 B.b.1,B.b.2 B.b.3,B.b.4	5 years
6	Pellet Injection Research Facility	200 M\$	A.a.3,A.b.1 A.c.1	5 years
7	Alternative DD Target Irradiation Facility (Upgrade Ω -Laser at UofR to 100 kJ)	100 M\$	A.a.1,A.a.3 A.b.1,A.c.1 B.a.1,B.a.2 B.a.3	5 years
Total Target R&D Costs		725M\$		

DT = deuterium/tritium fuel, TC = target chamber, DD = direct drive.

5.5.3.2 R&D for Feasibility of Laser Driven Direct Drive Target System

(Relevant Key Issues: A.a.1, A.a.3, A.b.1, A.c.1, B.a.1, B.a.2, B.a.3, B.a.4, B.a.5.)

Description of Problem - Designs for direct drive (DD) laser driven IFE DT targets have been anchored on experiments conducted on miniature DD targets illuminated with only a few kJ of laser energy. Large reactor sized, multi-MJ DD targets may require different illumination conditions making use of recent technological innovations in laser beam propagation and apodization. For reactor operation, the DD targets must also be accurately injected into the target chamber in coordination with a tracking/alignment system capable of meeting the illumination uniformity requirements.

Description of Required R&D Efforts - R&D work relevant to specific key issues associated with the Prometheus laser driver described here include:

- A.a.1 Direct Drive Target Coupling,
- A.a.3 Survivability of Targets in Target Chamber Environment,
- A.b.1 Demonstrating of Injection and Tracking of Targets Coupled with Beam Steering,
- A.c.1 Manufacturability of High Quality, Low Cost Direct-Drive and Indirect Drive Targets,
- B.a.1 DT Target Illumination Issues,
- B.a.2 Large Laser Development and Bandwidth Issues,
- B.a.3 Final Optics Pointing System,
- B.a.4 Grazing Incidence Mirror Damage,
- B.a.5 SBS Pulse Compressor,

Two general types of R&D experiments are required to solve the problems identified in the corresponding Critical Issue #2:¹

- (1) Full-scale DD target irradiation experiments
- (2) Realistic DD target injection, tracking, and alignment experiments

Each is briefly described below. (A combination of these two general types of R&D experiments is not recommended at this time as the costs would be prohibitive.)

Direct-Drive Target Irradiation Experiments at > 1 MJ - IFE target irradiation experiments on reactor-sized DD targets can be carried out using a single shot laser irradiation facilities such as that proposed for the Nova Upgrade. Laser driver energies of at least 1 MJ need to be delivered in approximately 60 beamlines with a ~1% illumination uniformity. Both tangential focusing and potentially more efficient, nested and apodized square beamlet DD target illumination configurations need to be investigated. Different laser driver prepulse shapes need to be investigated to ensure that undesirable stimulated Raman and Brillouin scattering processes in the underdense plasma atmosphere do not contribute to target preheating.

Direct-Drive Target Injection Experiments - A separate series of experiments needs to be conducted on DD target injection, tracking, and beam alignment to assure that the static DD target irradiation specifications can be met. This may necessitate the use of a "shine shield" on the DD IFE target.

Facility Requirements - Single-shot DD target irradiation experiments can yield useful data on target design, laser/target coupling, and the relative successes of tangential focusing vs. nested apodized beamlets on the DD targets. For full scale direct-drive laser target irradiation experiments, a new laser facility at least as large as the proposed Nova Upgrade laser irradiation facility will be required. A separate new facility will also be required to perform the target tracking and alignment experiments.

Cost and Schedule - The Nova Upgrade facility has been estimated to cost between \$300 M and \$400M.² If funded promptly, this IFE facility should be on-line by 1998,³ at which time DD experiments such as those described above could be carried out. The DD target experiments themselves, were they to be conducted in the Nova Upgrade facility, are could be completed in 18 months and are estimated to cost approximately \$25M (assuming two series of 100 DD targets shot @ \$50k/shot plus \$3M for experimental staff, \$10M for simulations/data reduction, and \$2M for diagnostics).

A relatively simple laboratory facility could be used to test DD target tracking and alignment techniques. With a \$500k laboratory conversion (of an existing laboratory) combined with \$1.5M for staff salaries and alignment diagnostics, attractive DD target alignment schemes could be tested. A separate source of DD targets (from a target fabrication laboratory) could furnish targets at an estimated cost of \$20K (for 2×10^4 DD targets).

Summary of R&D Cost Estimates

Table 5.5-4 Feasibility of Laser-Driven Direct-Drive Target System
 R&D Task and Duration Estimates

<u>No.</u>	<u>Task Description</u>	<u>Estimated Cost</u>	<u>Key Issue</u>	<u>R&D Duration</u>
1	Demo DD Target Survivability in TC	\$5 M	A.a.3	2 years
2	Demo Target Injection/Tracking	\$10 M	A.b.1,B.a.3	3 years
3	Target Manufacturability	\$10 M	A.c.1	2 years
4	Demo DD Target Beam Nesting	\$10 M	B.a.1	3 years
5	Satisfy Bandwidth Requirements	\$10 M	B.a.2	3 years
6	Laser Beam/Target Alignment System	1\$2 M	A.b.1,B.a.3	4 years
7	Demo DD MJ DT Target Ignition*	\$400 M	A.a.1,B.a.1	10 years
8	Final optics pointing demo	5 M\$	A.b.1,B.a.3	3 years
Total Laser Driver R&D Costs		\$459M		

*Includes cost of Nova Upgrade.

References for 5.5.3

1. Gary J. Linford, TRW S&TG/ATD, "ICFRDS Critical Issue #2: Feasibility of Laser Driven Direct Drive Targets," December 1991.
2. "Nova Upgrade Facility for Ignition and Gain," UCRL-LR-106874, Lawrence Livermore National Laboratory, Livermore, CA 94551 (March 1991).
3. "Nova Upgrade: A Proposed ICF Facility to Demonstrate Ignition and Gain by the Year 2000," UCRL-LR-106736, Lawrence Livermore National Laboratory, Livermore, CA 94551 (March 1991).

5.5.3.3 R&D for Feasibility of Heavy Ion Driven Indirect-Drive Target System

(Relevant Key Issues: B.b.1, B.b.2, B.b.3, B.b.4, B.b.5)

Description of Problem - The primary problems associated with the feasibility of heavy ion indirect-drive (HI ID) targets have to do with space-charge-limited heavy ion beam transport and accurate focusing onto the moving HI ID target. There is currently substantial disagreement among HI driver experts with regard to the conditions required for reliable self-focused HI channel formation, even assuming an ionizing precursor (either another charged particle beam or an ultraviolet [UV] laser beam). Furthermore, although calculations show that for two HI beam bundles (each having 3 MJ of 4 GeV lead ions), following passage through the stripping cells, the resulting MA beam current is above the threshold for self-pinching by about two orders of magnitude, the HI ID target experiments would need to be conducted at or near full scale to demonstrate the feasibility of the concept.

Another HI ID target problem is associated with fabricating the HI ID target to be economical, mechanically robust to withstand launch accelerations, and capable of meeting the precise target design requirements for efficient implosion.

Recommended R&D work associated with the Prometheus-H heavy ion driver include the following relevant key issues:

- B.b.1 Timing of Heavy Ion Beams,
- B.b.2 Heavy Ion Channel Formation,
- B.b.3 Heavy Ion Channel Transport,
- B.b.4 Stripping of Heavy Ion Beam,
- B.b.5 Alignment of Indirect Heavy Ion Target

Description of Required R&D Efforts - Seven types of HI ID R&D experiments are required to solve the problems identified in the corresponding Critical Issue #3:¹

- (1) Demonstration that ~12 to 18 lead HI beams can be accelerated to an energy of 4 GeV, injected and ejected efficiently from the storage rings in timed, synchronized, and bunched prior to injection into the triplet focusing magnets.

- (2) Demonstration that the 4 GeV (in a +2 charge state) can be focused down to a spot having a radius of 3 mm.
- (3) Demonstration that the focused HI beam will enter a preformed channel (formed by either a precursor ion beam or UV laser beam).
- (4) Demonstration that the self-pinch beam will self-focus and follow the preformed channel with an angular accuracy of ~10 microradians.
- (5) Efficiently convert the ~6 MJ of HI beam energy to soft X-rays in the target.
- (6) Demonstration that all return currents can be conducted without significant HI beam deflection or misalignment.
- (7) Demonstration that launched HI ID targets can (a) be directed accurately into the HI ID target firing zone, and (b) meet target robustness requirements.

There is some indication that HI ID target irradiation performance may be improved by single-sided HI ID target irradiation geometries but with the condition that the delivered HI beam energy (and hence the number of HI beams) may need to be reduced.

Acceleration and Transport of HI Beams - It will be necessary to demonstrate the efficacies of the entire single beam accelerator operated in a burst mode, together with the synchronized injection and ejection of beams from the storage rings. Demonstration of required HI beam bunching while minimizing beam losses prior to injection into the triplet focusing magnets.

Focusing of Bundled HI Beams to 3 mm Radius Spot - Injection of approximately a dozen synchronized, bunched, 4 GeV, doubly charged HI beams into the triplet focusing magnets, focusing the HI beams down through a neutralizing cell to achieve a 3 mm radius spot on an electron-stripping gas jet. The current in each of the two beamlines (assuming two-sided HI ID target irradiation) should easily exceed 1 MA after stripping. The focusing geometry must allow a precursor beam (either an ion beam or a UV laser beam) to pre-form the beam channel.

Injection of Focused HI Beams into Pre-formed Channel - By placing the common focus of the overlapping HI beams at the head of a pre-formed ionized channel, it is necessary to demonstrate the efficient capture (~90%) of the combined HI beams into a self-pinch channel. Beam currents of the order of 10 MA are expected.

Propagation of Self-Pinch HI Beams Parallel to Precursor Beam - The dynamic stability of the self-focused HI beams propagating over distances of the order of 5 m must be demonstrated. Propagation of the HI beams within the channel and parallel to the direction established by the precursor beams ~100 mrad must be demonstrated. Limits on interbeam energy imbalances and the effects of these interbeam energy imbalances on the propagation characteristics of the self-focused HI beam channel need to be determined.

Demonstration of Efficient Conversion of 3 MJ 4 GeV HI Beams to Soft X-rays - Full-scale HI ID target experiments must be conducted to demonstrate the required X-ray conversion efficiencies.

Demonstration of Self-Pinched HI Beam Insensitivity to Deflection - With the HI driver running in the burst mode, measurements of HI beam deflections as functions of return current symmetries need to be conducted to assess the effects of external currents reducing the effective pointing accuracies of the HI beams.

HI ID Target Tracking and Performance Verification - A separate series of experiments needs to be conducted on ID target injection, tracking, and beam alignment to assure that the static ID target irradiation specifications can be met. This may necessitate the use of "shine shields" on the two ends of the cylindrical ID IFE target in analogy with measurements required for similar laser-driven targets.

Facility Requirements - A few subscale HI ID experiments can be conducted at existing accelerator facilities. However, the majority of HI ID R&D experiments could only be conducted at a new accelerator site designed to support these HI experiments. This large accelerator facility can be used for conducting the extensive experimental measurements outlined above. Considerable modifications may be required during the course of the HI ID target experiments to modify the ramp gradient, fixed gradient, storage rings, buncher accelerator, and final focusing triplet configurations in accordance with varying HI ID target irradiation requirements. It is highly probable that as HI ID target experiments are conducted, design details of the HI ID targets will evolve, thereby necessitating continued modifications to the HI driver facility. The required accelerator facility would be substantially smaller than that of the proposed Superconducting Super Collider. A smaller facility could be used to perform the target tracking, alignment, and evaluation experiments. Some reconfiguration of these facilities would be required to generate the required target illumination symmetries.

Cost and Schedule - The estimated costs for supporting the ambitious plans defined above are highly dependent upon the availability of existing accelerator facilities. If it were necessary to construct such a facility from the ground up, enormous costs may be involved, possibly as much as \$700 M. Depending upon the evolution of optimum HI ID target illumination requirements, some time and money would be needed to reconfigure the accelerator and focusing magnets to meet specific configuration requirements. The HI ID target experiments themselves, could be completed in 18 months and are estimated to cost approximately \$20M (assuming two series of 100 ID targets shot @ \$40k/shot plus \$3M for experimental staff, \$7M for simulations/data reduction, and \$2M for diagnostics). These HI ID experiments could be performed in conjunction with the R&D experiments associated with cost reduction of a suitable IFE HI driver⁽²⁾. Additional experiments and costs are described below in Summary of R&D Cost Estimate.

For HI ID target injection experiments, a laboratory could be equipped for \$500k with a budget of \$1.5M to perform HI ID target injection experiments. Realistic ID targets

would be supplied by another target fabrication laboratory (to be determined) at an estimated cost of \$200k. Additional experiments and costs are described below in Summary of R&D Cost Estimates.

Summary of R&D Cost Estimates

**Table 5.5-5 Feasibility of Heavy Ion Driven Indirect Drive Target System
R&D Task and Duration Estimates**

<u>No.</u>	<u>Task Description</u>	<u>Estimated Cost</u>	<u>Key Issue</u>	<u>R&D Duration</u>
1	Demo DT Target Survivability in TC	\$5 M	A.a.3	2 years
2	Demo Target Injection/Tracking	\$10 M	A.b.1,B.a.3	3 years
3	Target Manufacturability	\$10 M	A.c.1	2 years
4	Demo Single Accel. in Burst Mode	\$15 M	B.b.1	3 years
5	Develop Bright Pb ⁺² Source	\$10 M	B.b.1	3 years
6	Develop high brightness HI injector	\$20 M	B.b.1	2 years
7	Demo low emittance through injector	\$10 M	B.b.1	2 years
8	SP HI Pulse Synch. & Timing Demo	\$10 M	B.b.1	3 years
9	SP Triplet Focusing Demo	\$10 M	B.b.2	2 years
10	SP HI Channel Formation Demo	\$100 M	B.b.2	7 years
11	SP Injection of HI Beam in Channel	\$10 M	B.b.3	3 years
12	SP Demo of Channel Transport @ MA	\$50 M	B.b.3	5 years
13	SP HI Beam Stripping	\$20 M	B.b.4	2 years
14	SP HI Neutralization	\$5 M	B.b.4	1 year
15	Develop high PRF burst-mode pwr.sup.	\$30 M	B.b.3	2 years
16	Demo superconducting quadrupoles	\$20 M	B.b.3	3 years
17	Demo storage ring performance	\$50 M	B.b.3	3 years
18	Demo bunchers	\$25 M	B.b.3	3 years
19	Develop HID Computer Control System	\$0 M	B.b.5	5 years
20	Alignment of HI Beam to ID Target	\$400 M	B.b.5	10 years
Total Heavy Ion R&D Costs		\$830 M		

References for 5.5.3.3

1. Gary J. Linford, "ICFRDS Critical Issue #3: Feasibility of Indirect Drive Targets for Heavy Ion," TRW S&TG/ATD, December 1991.
2. Alfred Maschke, Gary Linford, and Steven Fornaca, "Research and Development for Critical Issue #5: Cost Reduction for the Heavy Ion Driver," TRW S&TG/ATD, January 1992.

5.5.3.4 R&D for Feasibility of Laser Driven Indirect Drive Target System

(Relevant Key Issues: A.a.2, A.a.3, A.b.1, A.c.1, B.a.2, B.a.3, B.a.4.)

Description of Problem - Although more IFE indirect-drive target experiments have been conducted laser energies between 10 and 30 kJ than have been carried out for direct-drive targets, there remains a gap in laser irradiation energies of more than two orders of magnitude between the current experimental indirect-drive laser DT targets and the proposed IFE reactor-scale targets. Thus the current designs for reactor-scale indirect drive (ID) laser driven IFE DT targets have been anchored on experiments conducted on miniature ID targets illuminated with only a less than 1% of the laser energy required for the IFE reactor laser drivers. Furthermore, reduction or elimination of the transparencies¹ of the hohlraum entrance apertures may be an issue. As was the case also for direct-drive targets, for IFE reactor operation, it must be demonstrated that the ID targets can also be accurately injected into the target chamber with a tracking/alignment system capable of meeting the illumination requirements.

R&D work relevant to specific key issues associated with the Prometheus laser driver described here include:

- A.a.2 Indirect Drive Target Coupling
- A.a.3 Survivability of Targets in Target Chamber Environment
- A.b.1 Demonstrating of Injection and Tracking of Targets Coupled with Beam Steering
- A.c.1 Manufacturability of High Quality, Low Cost Indirect-Drive Targets
- B.a.1 DT Target Illumination Issues
- B.a.2 Large Laser Development and Bandwidth Issues
- B.a.3 Final Optics Pointing System
- B.a.4 Grazing Incidence Mirror Damage

Description of Required R&D Efforts - Two types of R&D experiments are required to solve the problems identified in the corresponding Critical Issue #4:²

- (1) Gradual scale up to full-scale ID target irradiation experiments.
- (2) Brassboard laser driven ID target injection, tracking, and alignment experiments.

Each is briefly described below:

Indirect-Drive Target Irradiation Experiments at >100 kJ to 1 MJ - Initial experiments need to be carried out at lower laser irradiation energies (~100 kJ) and various temporal formats to determine the ranges over which plasma closure of entrance apertures occurs. Then IFE target irradiation experiments on reactor-sized ID targets

can be carried out using single shot laser irradiation facilities such as that proposed for the Nova Upgrade. Laser driver energies ranging up to at least 1 MJ need to be delivered in two symmetric beam bundles with a ~5% illumination uniformity. Different prepulse shapes need to be investigated to ensure that plasma closure of the ID target entrance apertures and undesirable stimulated Raman and Brillouin scattering processes in the underdense plasma atmosphere generated inside the target do not reduce the target coupling efficiency or contribute to DT target preheating.

Indirect-Drive Target Injection Experiments - A separate series of experiments needs to be conducted on ID target injection, tracking, and beam alignment to assure that the static ID target irradiation specifications can be met. This may necessitate the use of "shine shields" on the two ends of the cylindrical ID IFE target. ID target robustness must also be demonstrated; i. e., following a ~200 g accelerated target launch, internal mechanical oscillations must be damped out such that the internal hohlraum components must be in proper position to meet ID implosion requirements.

Facility Requirements - A DT target laser irradiation facility at least as large as the proposed Nova Upgrade laser irradiation facility will be required to permit the needed single pulse laser driven ID target experiments to be performed.

A separate new facility will also be required to perform the target tracking and alignment experiments. Some reconfiguration of the facility would be required to generate the required target illumination symmetries. Since a similar target injection facility would be required for direct-drive target injection experiments, a single laboratory could be designed to serve both experiments if funding were available to perform both experiments. As indicated below, common use of the target injection facility is estimated to save approximately \$500K.

Cost and Schedule - The Nova Upgrade facility has been estimated to cost between \$300M and \$400M.³ If funded promptly, this IFE facility should be on-line by 1998,⁴ at which time ID target experiments such as those described above could be carried out. Depending upon the target illumination symmetries, some time and money would need to be expended to reconfigure the laser to meet specific requirements. The ID target experiments themselves, were they to be conducted in the Nova Upgrade facility, could be completed in 18 months and are estimated to cost approximately \$25M (assuming two series of 100 ID targets shot @ \$50K/shot plus \$3M for experimental staff, \$10M for simulations/data reduction, and \$2M for diagnostics). Significant cost savings could be realized by combining a test program with that described for direct-drive targets.⁵ Additional experiments and costs are described below in Summary of R&D Cost Estimate.

For target injection experiments, a laboratory could be equipped for \$500K with a budget of \$1.5M to perform target injection experiments. Realistic ID targets would be

supplied by another target fabrication laboratory (to be determined) at an estimated cost of \$200K. Additional experiments and costs are described below in Summary of R&D Cost Estimate.

Summary of R&D Cost Estimates

**Table 5.5-6 Feasibility of Laser-Driven Indirect-Drive Target System
R&D Task and Duration Estimates**

<u>No.</u>	<u>Task Description</u>	<u>Estimated Cost</u>	<u>Key Issue</u>	<u>R&D Duration</u>
1	Demo DT Target Survivability in TC	\$5 M	A.a.3	2 years
2	Demo Target Injection/Tracking	\$10 M	A.b.1,B.a.3	3 years
3	Target Manufacturability	\$10 M	A.c.1	2 years
4	Laser Beam/Target Alignment System	\$12 M	A.a.2,B.a.3	4 years
5	Demo DD MJ DT Target Ignition*	\$400 M	A.a.1,B.a.1	10 years
6	Final optics pointing demo	\$5 M	A.b.1,B.a.3	3 years
7	Optics Damage Resistance Demo	\$5 M	B.a.4	3 years
8	Develop Robust GIMM	\$5 M	B.a.4	4 years
Total Laser Driver R&D Costs		<u>\$452M</u>		

*Includes cost of Nova Upgrade.

References for 5.5.3.4

1. J. M. Auerbach, et al., "Closure Phenomena in Pinholes Irradiated by Nd: Laser Pulses," Applied Optics, 18, 510 (1979).
2. Gary J. Linford, "ICFRDS Critical Issue #4: Feasibility of Laser Driven Indirect Drive Targets," TRW S&TG/ATD, December 1991.
3. "Nova Upgrade Facility for Ignition and Gain," UCRL-LR-106874, Lawrence Livermore National Laboratory, Livermore, CA 94551 (March 1991).
4. "Nova Upgrade: A Proposed ICF Facility to Demonstrate Ignition and Gain by the Year 2000," UCRL-LR-106736, Lawrence Livermore National Laboratory, Livermore, CA 94551 (March 1991).
5. Gary J. Linford, Douglas Drake, and Dan Driemeyer, "R&D for Critical Issue #2 Feasibility of Laser Drive Direct Drive Target Systems," IFRDS Program, MDA, St. Louis, MO (1992).

5.5.3.5 R&D for Cost Reduction for the Heavy Ion Driver

(Relevant Key Issues: A.a.3, A.b.1, A.c.1, B.b.1, B.b.2, B.b.3, B.b.4, B.b.5)

Description of Problem - As described in the associated description provided as Critical Issue #5,¹ the major attraction of the Heavy Ion (HI) approach to inertial fusion energy (IFE) has always been related to the fundamental technical feasibility of building a HI driver system with the required properties to drive a DT pellet to ignition. The basic accelerator technology is well developed, the beam physics is tractable, and existing accelerator systems have exhibited 25 year lifetimes with 95% availabilities. A system to provide the required average power could have been built ten years ago. The major problem is cost. A 10 GeV linear accelerator built with today's technology would cost more than a billion dollars.

There are two key issues associated with HI driver cost reduction:

- (1) Space charge-limited transport of a bunched beam to minimize total length of the single beam LINAC (or multiple beam LINAC).
- (2) High current storage rings for heavy ion beams (required for single beam LINACs).

In addition, there is an important secondary issue having to do with the losses associated with Metglas (important for high pulse repetition rates in single beam LINACs).

Recommended R&D work associated with the Prometheus-H heavy ion driver include the following relevant key issues:

- A.a.3 Survivability of Targets in Target Chamber Environment
- A.b.1 Demonstrating of Injection and Tracking of Targets Coupled with Beam Steering
- A.c.1 Manufacturability of High Quality, Low Cost Indirect-Drive Targets
- B.b.1 Timing of Heavy Ion Beams
- B.b.2 Heavy Ion Channel Formation
- B.b.3 Heavy Ion Channel Transport
- B.b.4 Stripping of Heavy Ion Beam
- B.b.5 Alignment of Indirect Heavy Ion Target

Description of Required R&D Efforts - Three types of R&D experiments are required to solve the problems identified in the corresponding Critical Issue #5:¹

- (1) Development of cost effective techniques and demonstrations of space charge-limited transport of a bunched heavy ion beam through an accelerator,
- (2) Development of cost effective techniques and design of high current storage rings for heavy ion beams, and
- (3) Minimization of Metglas losses to raise the accelerator efficiency.

Each of these required R&D efforts is briefly described below:

R&D Demonstration of Space Charge-Limited Transport of a Bunched Beam -

Experiments and computer simulations have shown that transporting beams for several kilometers at their space charge limit should be possible, with little emittance growth. However, this HI beam transport has only been demonstrated with low energy, low power, unbunched beams. It is necessary to demonstrate transport at high σ_0 (undepressed tune), low σ (depressed tune), continually bunching the HI beam to increase current as voltage increases.

If the HI beams have to be transported at currents lower than the space charge limit, then the accelerator will have to have a longer pulse (in the case of a single beam LINAC) or more quadrupole transport channels within the same multiple beam accelerator, thereby increasing the cost of the accelerator.

R&D Demonstrations of High Current Storage Rings for Heavy Ion Beams - One of the characteristic properties of linear accelerators is their ability to run at rather high average powers and relatively high repetition rates. Since the clearing time in the ICF reactor precludes very high repetition rates for the DT pellet ignition, the LINAC is forced to operate at uneconomical repetition rates. This problem can be eliminated if the beams for the LINAC can be stored for a short period of time. By operating the induction LINAC in the burst mode, the induction cores are used over and over, and, of course, each core is therefore smaller in diameter.

The issue here is one of demonstrating that a HI beam of the required intensity can be stored in a storage ring for the requisite time, typically on the order of 1 to 2 milliseconds. The issues are similar to those associated with bunched beam transport, but have the additional complications associated with closed orbit synchrotrons, such as betatron and synchrotron resonances, etc., which can give rise to emittance growth or beam loss. Furthermore, beam induced vacuum instability is another problem which must be overcome. All of these issues can only be resolved with an experimental ring with parameters reasonably close to what is required.

R&D Experiments to Reduce Metglas Losses - The first type of loss in Metglas, that due to BH hysteresis losses may be intrinsic and is probably unavoidable, although further investigations into use of less hysteretic ceramic materials may be very useful. The second type is eddy current loss in the magnet cores which can be minimized by careful core design and attention to detail in proper pulse shaping of the current waveforms. The important physical parameter associated with the eddy current losses is the thickness of the Metglas ribbon and the shape and amplitude of the waveform used. Presently Metglas thicknesses of the order of 35 μ are being employed, although successful experiments have been carried out with Metglas thicknesses as small as 20 μ . By optimizing the voltage waveforms used to drive the beam and to reset the cores, the pulsed power requirements can be minimized.

Facility Requirements - In order to demonstrate the two key HI driver R&D issues, transport of a bunched, space charge-limited HI beam and demonstration of high current HI storage rings will require either the use of an existing suitable induction LINAC or the construction of a new facility capable of meeting the HI driver requirements of transporting megajoules of energy in doubly charged, non-relativistic ~5 GeV lead ions. Assuming typical accelerator gradients of the order of 1 MeV/m, an accelerator having dimensions of several kilometers will be required. In addition, approximately two dozen high current storage rings having diameters of the order of 50 m will be required to investigate technologies associated with achieving the required performance levels while minimizing the cost of the storage rings.

A significant demonstration of the HI beam transport and storage ring configuration could be carried out using a single pulse, a single ring, reduced energy (to possibly 0.5 GeV), pulsed magnets, etc. Such a facility could be installed in the Advanced Test Accelerator Site 300 facility at the Lawrence Livermore National Laboratory (LLNL) at a relatively small cost.

The requirements for the Metglas investigations are even more modest. The required R&D investigations to reduce Metglas losses can be carried out at a variety of accelerator facilities, such as those existing at the Lawrence Berkeley Laboratory (LBL), LLNL, Fermilab, Brookhaven National Laboratory, Argonne National Laboratory, etc.

Support of HI indirect-drive target experiments requires a full-scale HI driver, but a HI driver that runs at a relatively low repetition rate. Thus a major facility advantage would be a significant reduction in installed power requirements since the single beam LINAC would not need to operate at 5 Hz.

Cost and Schedule - The costs associated with carrying out the ambitious HI cost reduction R&D experiments are a strong function of whether or not it would be necessary to construct a new facility to meet the demanding HI driver requirements with regard to beam current, beam energy, particle energy, atomic weight of ions, etc. It is estimated that the total cost to build a conventional induction LINAC with two dozen storage rings to accomplish the R&D experiments would be of the order of \$1000M. The experiments themselves would be relatively expensive if promising techniques for reducing cost required frequent rebuilding of the accelerator and storage rings. Such a facility could be constructed in five years once a suitable site had been selected. It would also be a very attractive solution to have this large HI driver facility support the related HI indirect drive target feasibility R&D experiments proposed as R&D Program #3.² It is estimated that significant Metglas development could continue at one or more accelerator facilities with a funding level of \$1-2M/year. Additional experiments and costs are described below in Summary of R&D Cost Estimate.

Summary of R&D Cost Estimates

**Table 5.5-7 Cost Reduction in the Heavy Ion Driver
R&D Task and Duration Estimates**

<u>No.</u>	<u>Task Description</u>	<u>Estimated</u>	<u>Key Issue</u>	<u>R&D</u>
		<u>Cost</u>		<u>Duration</u>
1	Demo DT Target Survivability in TC	\$5 M	A.a.3	2 years
2	Demo Target Injection/Tracking	\$10 M	A.b.1,B.a.3	3 years
3	Target Manufacturability	\$10 M	B.b.1	3 years
5	Develop Bright Pb ⁺² Source	\$10 M	B.b.1	3 years
6	Develop high brightness HI injector	\$20 M	B.b.1	2 years
7	Demo low emittance through injector	\$10 M	B.b.1	2 years
8	SP HI Pulse Synch. and Timing Demo	\$10 M	B.b.1	3 years
9	SP Triplet Focusing Demo	\$10 M	B.b.2	2 years
10	SP HI Channel Formation Demo	\$100 M	B.b.2	7 years
11	SP Injection of HI Beam in Channel	\$10 M	B.b.3	3 years
12	SP Demo of Channel Transport @ MA	\$50 M	B.b.3	5 years
13	SP HI Beam Stripping	\$20 M	B.b.4	2 years
14	SP HI Neutralization	\$5 M	B.b.4	1 year
15	Develop high PRF burst-mode pwr.sup.	\$30 M	B.b.3	2 years
16	Demo superconducting quadrupoles	\$20 M	B.b.3	3 years
17	Demo storage ring performance	\$50 M	B.b.3	3 years
18	Demo bunchers	\$25 M	B.b.3	3 years
19	Develop HID Computer Control System	\$20 M	B.b.5	5 years
20	Alignment of HI Beam to ID Target	\$400 M	B.b.5	10 years
Total Heavy Ion R&D Costs		\$845M		

References for 5.5.3.5

1. Alfred Maschke, "ICFRDS Critical Issue #5: Cost Reduction for the Heavy Ion Driver," TRW S&TG/ATD, December 1991.
2. Gary Linford, Douglas Drake, and Dan Driemeyer, "Research and Development for Critical Issue #3: Feasibility of Indirect Drive for Heavy Ion," IFRDS, MDA, January 1992.

5.5.3.6 R&D for Demonstration of High Overall Laser System Efficiency

(Relevant Key Issues: B.a.1, B.a.2, B.a.3, B.a.5)

Description of Problem - As discussed in Critical Issue #6,¹ the inertial fusion energy (IFE) excimer laser driver system is composed of a number of components which can individually be optimized to yield high efficiencies. The achievement of high operating efficiency is a crucial requirement for the laser driver. Another crucial goal is the development of highly reliable laser driver components. A laser driver that frequently fails will not permit economical IFE reactor operation to be achieved.

The MDA Team Prometheus Reactor Design Study KrF laser driver consists of the following four major elements:

- (1) The excimer laser amplifiers
- (2) The Raman accumulators
- (3) The SBS pulse compressors
- (4) The computer controlled and self-aligning linear optical train which directs the laser beams through the various optical components and down into the target chamber.

Significant research and developmental work needs to be performed on the excimer laser amplifier modules. Although there are still R&D issues to be settled, the latter three elements listed above require less additional technological development and experimental verification before they can be judged adequate to be incorporated into a mature laser driver design.

R&D work relevant to specific key issues associated with the Prometheus laser driver described here include:

- B.a.1 DT Target Illumination Issues,
- B.a.2 Large Laser Development and Bandwidth Issues,
- B.a.3 Final Optics Pointing System,
- B.a.5 SBS Pulse Compressor,

The Excimer Laser Amplifier Problem - The fundament of an efficient, reliable Prometheus laser driver is the successful design, construction, and testing of excimer laser amplifier modules. The MDA team has found that large excimer laser amplifiers producing >50 kJ of energy may prove to be undesirable for a reactor since the loss of a single excimer laser amplifier would prevent the ~1% direct drive (DD) target illumination uniformity requirement from being achieved. Furthermore, excimer laser amplifiers generating large (>50 kJ) energies also require excitation geometries of unwieldy (~2x2x4 m) dimensions, amplified spontaneous emission (ASE), and parasitic oscillations can reduce laser efficiencies, threaten the safety of the cryogenic target, and complicate the overall optical design of the laser driver. As a consequence, the MDA team has identified a moderate excimer laser amplifier output energy range (from 4 to 6 kJ) as being optimum for constructing an efficient, reliable, and safe IFE laser driver capable of tolerating an occasional amplifier failure without forcing reactor shutdowns. Each of these reduced scale excimer laser amplifiers has modest dimensions (0.3x0.3x2 m). This 4-6 kJ energy level, however, is much lower than the ~100 kJ needed for each of the 60 laser driver beamlines. In order to achieve the requisite beam energies (~100 kJ), the MDA team has selected to combine many excimer beams coherently using Raman accumulators.

During the past five years, relatively little work has been carried out in the USA with regard to improving the efficiency and the reliability of such moderate sized excimer laser amplifiers. Some analytical studies² have been carried out on both electron-

beam excited excimer lasers (EBEELs) and electron-beam sustained electric discharge lasers (EBSEDs) which offered (on paper) gross wallplug efficiencies as high as 17%. These efficiencies, however, are more likely to be reduced significantly if incorporated into a large laser system architecture. The main concern is that no experimental work in excimer amplifier development is either currently in progress or planned by the Department of Energy.

Work in the Soviet Union with sliding discharge cathodes, plasma electrodes, and UV pre-ionization in both excimer and CO₂ discharge lasers has produced some promising results^{3,4,5} which may offer alternatives to the EBSEDs. Although significant experimental work needs to be carried out to demonstrate the potentially higher efficiency of EBSEDs, the electric discharge lasers may offer an inherently higher efficiency than the EBEELs since excitation of the excimer species occur along the neutral channel, thereby avoiding the excitation of a large number of higher-lying states (which may contribute relatively little to the overall amplifier extraction efficiency) or which end up as excess heat which deleteriously affects excimer amplifier beam quality. Moreover, by avoiding transmitting large electron beam currents through foils, hibachis, etc., the overall excimer laser pumping efficiency may be significantly higher.

Raman Accumulator Problems - A key to achieving high efficiency with Raman accumulators is to start with a design that exhibits a high quantum efficiency, ξ , together with a large Raman gain coefficient, g_R . Stimulated rotational Raman gain in H₂ (or D₂) has been previously investigated and promises to fulfill the requirements for both ξ and g_R . Since the Raman accumulators are also expected to be operated in the crossed Raman configuration (to improve the beam quality of the output Stokes beam), some inefficiencies arise. The Raman accumulators need to be driven with a synchronized Stokes seed having appropriate temporal and spectral components. The primary R&D problem is to demonstrate efficient beam combination with high beam quality while suppressing parasitic oscillations and higher order Stokes components from being generated. Secondary Raman accumulator problems have to do with details associated with efficient generation of synchronized Stokes seeds which are correlated⁶ with the excimer pump beams.

Problems Associated with the Stimulated Brillouin Pulse Compressor - The stimulated Brillouin scattering (SBS) process when applied to the problem of temporally compressing long (>250 ns) excimer/Raman accumulator laser pulses tends to produce subnanosecond pulses² with high efficiencies (>95%). When a longer pulse (such as the 6 ns main pulse specified by the TWG) is required, the needed compressed pulse length can be generated by a ramped-Stokes seeded SBS cell, but at considerable cost of overall efficiency. Since the sum of the energies of the compressed 6 ns pulse and the long undepleted (>250 ns) pulse is approximately 100% of the original long excimer/Raman accumulator pulse, the overall efficiency of the ramped-Stokes seeded SBS cell can be improved by utilizing the long,

undepleted pump pulse as the long precursor pulse to the target (as specified by the TWG).⁷ The following operational details need to be demonstrated in an R&D program:

- (1) Demonstration of the performance (efficiency, pulse shape versatility, etc.) of a ramped Stokes seeded SBS cell.
- (2) Control over competing processes, parasitic oscillations, multi-order Stokes, etc.
- (3) Demonstration of the use of an electro-optical switchyard, pulse delay lines, etc., for utilizing depleted pump as the precursor pulse.
- (4) Performance of electro-optical "chirper" SBS Stokes seed generators.

Computer-Control and Alignment Problems - The computer control system must monitor an excimer master oscillator driving ~1000 excimer laser amplifier modules feeding into 60 Raman accumulators, 60 SBS pulse compressors, and 60 beam alignment systems attempting to strike a 6 mm diameter target moving at a speed of 200 m/sec., it is evident that a sophisticated parallel processing computer control system is required.

Description of Required R&D Efforts

Excimer Laser Amplifier R&D - R&D investigations of promising (efficient and reliable) designs of both electron beam excited excimer lasers (EBEELs) and electric-discharge excimer lasers (EDELs) need to be carried out.

EBEEL R&D - In the case of the EBEELs, the primary parameters to be demonstrated are reliability (mean number of shots between failures $>10^9$) and efficiency. Many of the color-center formation problems, chemical attack problems, etc., are similar to those described below for the EBELs.

EBSEDL R&D - Since the EBSEDL has received significantly less R&D in the past than the EBEEL, there are several problems associated with the EBSEDLs which require further experimental work. These include:

- (1) Characterization of the optimum pulse duration and gas mixture to achieve efficient neutral channel excimer excitation with a matched, efficient, pulsed power system.
- (2) Sensing and prevention of the formation of arcs in the discharges caused by consumption of fluorine, impedance changes, etc.
- (3) Extension of the operating lifetimes of the amplifiers to reach levels of 10^9 to 10^{10} amplifier firings between failures.
- (4) Control of color center formation and chemical attack of amplifier windows during the 10^9 to 10^{10} shot operational periods.

These problems need to be analyzed theoretically and solutions found experimentally during a series of R&D related technological development programs granted by DOE to industry and the national labs. The direct result of this R&D would permit the excimer laser amplifiers to become the workhorse of the Prometheus excimer laser driver by the year 2030.

R&D for Alternative Laser Drivers - R&D efforts to evaluate other efficient and reliable laser drivers should also be planned. These alternative IFE laser drivers could include:

- (1) Semiconductor diode pumped solid-state lasers ($\lambda = 1064$ nm).
- (2) Chemical oxygen-iodine lasers ($\lambda = 1315$ nm).
- (3) HF overtone chemical lasers ($\lambda \sim 1350$ nm).

These lasers require implementation of high average power harmonic conversion technology to permit efficient operation in the UV portion of the spectrum, but the ultimate reliabilities of these alternative fusion laser drivers may be higher than can be achieved with either EBEEs or EBSEDs.

Raman Accumulator R&D - The R&D program for the Raman accumulator is relatively simple and straightforward. It builds upon the extensive work already completed. Two types of Raman accumulator systems need to be addressed: single pulse and high repetition rate.

Single Pulse Raman Accumulator R&D - The following single pulse Raman accumulator tasks need to be addressed:

- (1) Demonstration of efficient rotational Raman conversion in H_2 (or D_2).
- (2) Demonstration of an effective (correlated) rotational Raman Stokes seed generator.
- (3) Demonstration of intensity averaging and beam quality enhancement for crossed Raman accumulator geometries.
- (4) Coherent, large aperture beam synthesis.
- (5) Control of diffraction and egg-crate damage by image relay optics.

Although some of these tasks can be demonstrated at sub-scale energies, the most convincing single pulse Raman accumulator R&D plan would involve a full, 100 kJ beamline.

Repetition Rate Raman Accumulator R&D - These R&D experiments need to deal primarily with the gas circulation problems to remove the phonon heat from the H₂ (or D₂) gas without adversely affecting the accumulator beam quality.

SBS Pulse Compressor R&D - In a manner analogous to the Raman accumulator described above in Section 2.3, the SBS pulse compressor R&D needs to be divided between single pulse proof-of-principle experiments and high average power experiments dealing with control of thermal effects.

Single Shot SBS Pulse Compressor R&D - Both sub-scale and full scale single shot R&D SBS pulse compressor experiments need to be performed. The fundamental working principles of the SBS pulse compressor can be demonstrated in sub-scale experiments. These sub-scale experiments involve full scale physical lengths of the SBS cell ($L_{\text{cell}} = c\tau_{\text{pump}}/2$) but, to reduce costs, subapertures of perhaps 1/20 full aperture may be employed. These subscale SBS R&D experiments would include the following tasks:

- (1) Demonstration of high pulse compression conversion efficiency using a self-seeded, "chirped" input Stokes SBS seed.⁸
- (2) Demonstration of versatile SBS pulse compressor output pulse shapes by using a ramped "chirped" Stokes SBS seed, and
- (3) Demonstration of the operating principles of an electro-optical "switchyard" involving fast Pockels cells to tailor the undepleted pump pulse into an 80 ns long precursor pulse.

These experiments could be carried out at convenient apertures (~5 cm) using pulse energies of 250 J and 250 ns durations.

In order to conduct the full scale SBS Pulse Compressor R&D experiments, it would be necessary to have large aperture pump beams containing ~100 kJ. The MDA IFRDS SBS Pulse Compressor design features a relatively large aperture, ~1 m. Although this large 1 m aperture can be synthesized from an array of smaller optics supported in an "egg-crate" structure. These full scale experiments would be similar to the sub-scale experiments with the additional feature that transverse SBS parasitics could be investigated as a potential problem.

High Average Power SBS Pulse Compressor R&D Experiments - As described above for the single shot SBS pulse compressor R&D experiments, both subaperture and full aperture high average power R&D experiments can be performed. Since the primary purpose of the high average power experiments is to investigate the influence of phonon-induced thermal effects in the SF₆-filled SBS cell, it is very likely that only subaperture high average power experiments would produce meaningful results for the relative costs.

Computer Control and Alignment R&D Experiments - The computer control and alignment R&D experiments need to cover all aspects of computer control and optical alignment of the MDA Prometheus laser driver system. A variety of techniques has been suggested for performing the difficult moving DT target tracking and alignment tasks using interferometric and holographic techniques. These proposed tracking and alignment techniques require extensive real time, fast response, data processing, possibly requiring a series of dedicated parallel processors, artificial intelligence, expert systems, etc. The R&D program would have to demonstrate adequate performance of these (and other) control designs.

Facility Requirements

Excimer Laser Amplifier R&D Facilities - The facilities required to evaluate the performance of moderate energy (4-6 kJ) excimer laser modules are relatively modest. Assuming these amplifiers were 10% efficient and operated at a pulse repetition rate of 5 Hz, power supplies of ~500 kW would suffice to power the test amplifier.

Since one of the key design issues to be demonstrated for these excimer laser modules, it is essential that a large number of amplifiers be tested in parallel at as high a repetition rate as reasonable. The facilities would have to be designed to accommodate automatic, 24-hour per day operation in order to permit the evaluation of mean number of amplifier firings between firings of 10^9 and 10^{10} .

Raman Accumulator R&D Facilities - The single shot subscale Raman accumulator R&D experiments can be performed with modest laboratory facilities.

The high average power Raman accumulator R&D experiments would require significant input powers from excimer pump amplifiers. If an entire single beam of the laser driver were to be tested, an input energy/pulse of approximately 100 kJ would be required, possibly in the form of either 25 (5x5) 4 kJ excimer laser modules or 16 (4x4) 5.5 kJ excimer laser modules. These experiments could be combined with tests of test excimer laser amplifiers to realize significant cost savings. The full scale Raman accumulators would have apertures of ~1 m and lengths of the order of 10 m.

SBS Pulse Compressor R&D Facilities - The single pulse, subaperture SBS pulse compressor R&D facilities can be performed in a modest laser facility having a long optical path (~50 m) available. For a square 5 cm aperture SBS cell pumped with a Raman accumulator pulse of duration 250 ns and energy of 250 J, a cell length of approximately 38 m would be required.

Full aperture, high average power SBS compressor R&D facilities are similar to those described above for the high average power Raman accumulator experiments with the

additional requirement that sufficient laboratory space be provided for the 38 m long SBS pulse compressor cells.

Computer Control and Alignment R&D Facilities - Relatively modest facilities are required to test the computer control and alignment facilities. Since the most stressing R&D task is the tracking of the moving DT targets, the testing of this capability could be combined with a facility used for testing the DT target launching system.

Cost and Schedule

Costs of Excimer Laser Amplifier R&D - It is estimated that a minimum of \$20M and three years would be required to develop candidate excimer laser modules. Additional time and expense would be required to test the amplifiers to demonstrate 10^9 to 10^{10} firings between failures.

In order to demonstrate a single beam line, it would be necessary to construct between 20 and 40 of the excimer laser modules (depending upon their output energies), together with their associated pulsed power. It is estimated that this task would cost approximately \$80M once an excimer laser amplifier design had been perfected.

Cost of Raman Accumulator R&D Experiments - Single pulse, subscale Raman accumulator R&D experiments can be performed for \$2M. High repetition rate subscale Raman experiments would cost \$7M. Combined with the construction of an array of NxN excimer amplifiers described in Section 4.1, above, a full aperture 1x1 m Raman accumulator could be tested for an additional \$20M for a total of \$100M (NxN excimer amplifiers + Raman accumulator). This would take an estimated five years from beginning to end.

Cost of SBS Pulse Compressor R&D Experiments - The subaperture single SBS pulse compressor experiments could be carried out for \$4M over a two-year period. Full aperture, high average power tests of a full scale SBS pulse compressor could be carried out in association with construction of a NxN excimer laser pump array in (excimer laser modules) and a full aperture, high average power Raman accumulator (Raman Accumulator R&D) for an additional \$20M for a total cost of \$120M (\$80M for the excimer lasers, \$20M for the Raman experiments, and \$20M for the SBS experiments). This is estimated to take eight years from beginning to end.

Cost of Computer Control and Alignment R&D Experiments - It is recommended that these R&D experiments be conducted subscale with the predominant emphasis on testing the target tracking and alignment system. This task is estimated to cost \$20M in conjunction with a full scale DT target launching system.

Summary of R&D Cost Estimates

**Table 5.5-8 Demonstration of High Overall Laser System Efficiency
R&D Task and Duration Estimates**

<u>No.</u>	<u>Task Description</u>	<u>Estimated</u>	<u>Key Issue</u>	<u>R&D</u>
		<u>Cost</u>		<u>Duration</u>
1	Demo DD Target Beam Nesting	\$10 M	B.a.1	3 years
2	Satisfy Bandwidth Requirements	\$10 M	B.a.2	3 years
3	Laser Beam/Target Alignment System	\$12 M	A.b.1,B.a.3	4 years
4	Final optics pointing demo	\$5 M	A.b.1,B.a.3	3 years
5	Develop excimer laser modules	\$20 M	B.a.2	3 years
6	Test to demonstrate 10 ⁹ lifetime	\$40 M	B.a.2	5 years
7	Demonstrate single 6 kJ beam line	\$80 M	B.a.2	4 years
8	Demonstrate 6x16=96 kJ beam line	\$120 M	B.a.2	2 years
9	Develop/Demo Laser Control System	\$40 M	B.a.2	5 years
10	Develop 50 J Raman seed generators	\$2 M	B.a.2	1 year
11	Demonstrate 6 kJ Raman converter	\$1 M	B.a.2	1 year
12	Demo 100 kJ Raman converter	\$20 M	B.a.2	2 years
13	Develop programmable SBS chirper	\$2 M	B.a.5	1 year
14	Subscale SBS PC demonstration	\$2 M	B.a.5	1 year
15	Develop Large Aperture SBS chirper	\$10 M	B.a.5	3 years
16	Demo 6 kJ SBS Pulse Compressor	\$5 M	B.a.5	2 years
17	Demonstrate 100 kJ PC	\$20 M	B.a.5	3 years
18	Dev.Large Aperture Fast Pockels Cells	\$20 M	B.a.5	5 years
Total Laser Driver R&D Costs		<u>\$419M</u>		

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5.5.3.7 R&D for Reliability and Lifetime of Laser and Heavy Ion Drivers

(Relevant Key Issues: A.a.1, A.b.1, B.a.1, B.a.2, B.a.3, B.a.4, B.a.5, B.b.1, B.b.2, B.b.3, B.b.4, B.b.5)

Description of Problem - Both the Laser Driver (LD) and Heavy Ion Drivers (HID) for an inertial fusion energy (IFE) reactor will be required to operate reliably at approximately a 5 Hz rate over extended periods of time (of the order of years) in order not to impact adversely the IFE reactor cost of electricity (COE). This reliability requirement (corresponding to $\lambda = 1.58 \times 10^8$ shots/year) calls for robust driver designs exhibiting either remarkable durability or capable of being repaired and maintained on-line without requiring IFE reactor shut-down. Each of these two driver designs exhibits different reliability problems, and these reliability problems will be briefly described below. R&D work relevant to specific key issues associated with the laser and target described here include: A.a.1, Direct Drive Target Coupling, A.b.1, Demonstration of Injection and Tracking of Targets Coupled with Beam Steering, B.a.1, DT Target Illumination Issues, B.a.2, Large Laser Bandwidth Issues, B.a.3, Final Optics Pointing System, B.a.4, Grazing Incidence Mirror Damage, and B.a.5, SBS Pulse Compressor. Recommended R&D work relevant to key issues associated with the heavy ion driver include: B.a.1, Timing of Heavy Ion Beams, B.a.2, Heavy Ion Channel Formation, B.a.3, Heavy Ion Channel Transport, B.a.4, Stripping of HI Beam, and B.a.5, Alignment of Indirect HI Target.

KrF Laser Driver Lifetime Issues - The primary lifetime problem to be solved for the KrF excimer laser driver (LD) is associated with the pulsed excimer laser amplifiers. Secondary reliability problems associated with damage protection for optical components, gas circulation systems for Raman accumulators, etc., which require relatively little R&D to improve.

Two types of excimer laser amplifiers have been considered for the Prometheus IFRDS KrF laser driver: e-beam excited excimer laser amplifiers (EBEELs) and e-beam sustained electric discharge excimer lasers (EBSELs). The former has been subjected to substantial research and development but the latter (EBSELs) need substantial further development before the technology could be described as mature.

Our current data on the mean number of EBEL firings between failures indicates that this type of excimer laser amplifier is currently not capable of meeting a 2×10^8 firings between failures. The second type of excimer laser, EBSEL, has no significant experimental data regarding reliability, but the EBSEL theoretically appears to be potentially more reliable since the e-beams are not required to operate at high current through foils, hibachis, etc. The MDA Prometheus team selected a excimer laser/Raman accumulator driver which could tolerate occasional (one per month) failures of individual amplifier modules without compromising overall IFE reactor operation.

As a key KrF laser driver reliability issue, the Prometheus team has found that large excimer laser amplifiers producing >50 kJ of energy may prove to be undesirable for a IFE reactor since the loss of a single excimer laser amplifier would prevent the $\sim 1\%$ direct drive (DD) target illumination uniformity requirement from being achieved. Furthermore, excimer laser amplifiers generating large (>50 kJ) energies also require excitation geometries of unwieldy ($\sim 2 \times 2 \times 4$ m) dimensions, amplified spontaneous emission (ASE), and parasitic oscillations can reduce laser efficiencies, threaten the safety of the cryogenic target, and complicate the overall optical design of the laser driver. As a consequence, the MDA team has identified a moderate excimer laser amplifier output energy range (from 4 to 6 kJ) as being optimum for constructing an efficient, reliable, and safe IFE laser driver capable of tolerating an occasional amplifier failure without forcing reactor shutdowns. Each of these reduced scale excimer laser amplifiers has modest dimensions (0.3x0.3x2 m). This 4-6 kJ energy level, however, is much lower than the ~ 100 kJ needed for each of the 60 laser driver beamlines. In order to achieve the requisite beam energies (~ 100 kJ), the MDA team has selected to combine many excimer beams coherently using Raman accumulators. R&D experiments improving the performance of Raman accumulators have been recommended,¹ but since the reliabilities of these devices are well established, no additional R&D is required to increase the reliabilities of the Raman accumulators further.

During the past five years, little or no research has been carried out in the USA with regard to improving the efficiency and the reliability of 4-6 kJ excimer laser amplifiers. Some analytical studies² have been carried out on both electron-beam excited excimer lasers (EBELs) and electron-beam sustained electric discharge lasers (EBSEDs) which offered (on paper) gross wallplug efficiencies as high as 17%. These efficiencies, however, are more likely to be reduced significantly if incorporated into a large laser system architecture.

Work in the Soviet Union with sliding discharge cathodes, plasma electrodes, and UV pre-ionization in both excimer and CO_2 discharge lasers has produced some promising results^{3,4,5} which may offer alternatives to the EBSEDs. Although significant experimental work needs to be carried out to demonstrate the potentially

higher efficiency of EBSEDs, the electric discharge lasers may offer an inherently higher reliability and efficiency than the EBELs since excitation of the excimer species occur via an electric discharge along the neutral channel, thereby avoiding the excitation of a large number of higher-lying states (which may contribute relatively little to the overall amplifier extraction efficiency) or which end up as excess heat which deleteriously affects excimer amplifier beam quality. Moreover, by avoiding transmitting large electron beam currents through foils, hibachis, etc., the overall excitation efficiency of the excimer laser can be increased while, at the same time, eliminating a potential failure mode (i.e., foil rupture). The fundament of an efficient, reliable Prometheus laser driver is the successful design, construction, and testing of excimer laser amplifier modules.

Heavy Ion Driver Lifetime Problems - Although the HID basic accelerator technology is well developed, the beam physics is tractable, and existing accelerator systems have exhibited 25-year lifetimes with 95% availabilities, there are a number of unanswered questions associated with improving known weak links in the HID. Unlike the laser system, failure of almost any single component of the HID is likely to provoke a complete shutdown of the IFE reactor. A major lifetime problem to be solved for the HID has to do with analyzing to what extent redundant or backup systems could be implemented to prevent HID failure and consequent reactor shutdown.

There are a number of HID problems which should be investigated:

- (1) High reliability high brightness, doubly charged lead source
- (2) Reliability of helium refrigerators, cryostats, and individual magnets for superconducting magnets
- (3) Reproducibility of space charge limited transport of a bunched beam
- (4) Long term stabilities of high current storage rings for heavy ion beams
- (5) Reliability of Metglas to breakdown and long term deterioration

Description of Required LD and HID R&D Efforts - The R&D requirements for each of these HID problems is briefly discussed below.

Excimer Laser Amplifier R&D - R&D investigations of reliable and efficient designs of both electron beam excited excimer lasers (EBELs) and e-beam sustained electric-discharge excimer lasers (EBSEDs) need to be carried out. If funding is restricted, emphasis should be given the development of EBSEDs since they promise to be more reliable and efficient.

EBEL R&D - In the case of the EBELs, the primary parameters to be demonstrated are reliability (mean number of shots between failures $>10^9$) and efficiency. Many of the color-center formation problems, chemical attack problems, etc., are similar to those described below for the EBELs.

EBSEDL R&D - Since the EBSEDL has received significantly less R&D in the past than the EBDEL, there are several problems associated with the EBSEDLs which require further experimental work. These include:

- (1) Characterization of the optimum pulse duration and gas mixture to achieve reliable, efficient neutral channel excimer excitation with a matched, efficient, pulsed power system.
- (2) Sensing and prevention of the formation of arcs in the discharges caused by consumption of fluorine, impedance changes, etc.
- (3) Extension of the operating lifetimes of the amplifiers to reach levels of 10^9 to 10^{10} amplifier firings between failures.
- (4) Control of color center formation and chemical attack of amplifier windows during the 10^9 to 10^{10} shot operational periods.

These problems need to be analyzed theoretically and solutions found experimentally during a series of R&D related technological development programs granted by DOE to industry and the national labs. The direct result of this R&D would permit the excimer laser amplifiers to become the workhorse of the Prometheus excimer laser driver by the year 2030.

R&D for Alternative Laser Drivers - Extremely reliable pulsed excimer laser amplifiers may prove difficult to construct. Thus R&D efforts to evaluate other efficient and potentially more reliable laser drivers should also be planned. These alternative IFE laser drivers could include:

- (1) Semiconductor diode pumped solid-state lasers ($\lambda = 1064$ nm).
- (2) Chemical oxygen-iodine lasers ($\lambda = 1315$ nm).
- (3) HF overtone chemical lasers ($\lambda \sim 1350$ nm).

None of these alternative laser sources requires the use of high voltage, pulsed power. These near infrared lasers require implementation of high average power harmonic conversion technology to permit efficient operation in the UV portion of the spectrum, but the ultimate reliabilities of these alternative fusion laser drivers may be higher than can be achieved with either EBDELs or EBSEDLs.

R&D Reliability Demonstration Experiments for Heavy Ion Driver - Five types of R&D experiments are required to solve the HID potential reliability problems identified above:

- (1) Development of a reliable, high brightness, doubly charged lead ion source.
- (2) Demonstration of a highly reliable (possibly redundant) helium refrigeration system, serviceable cryostats, dependable magnets.

- (3) Development of reliable, cost effective techniques and demonstrations of space charge-limited transport of a bunched heavy ion beam through an accelerator.
- (4) Development of reliable, cost effective techniques and design of high current storage rings for heavy ion beams.
- (5) Minimization of Metglas deterioration while minimizing losses to raise the accelerator efficiency.

Each of these required R&D efforts is briefly described below:

Reliable R&D High Brightness Pb⁺⁺ Ion Development - At the present time, no reliable high brightness doubly charged lead ion source is available for providing input to the ramp gradient section of the HID. Redundant systems are recommended here in order to eliminate single point ion-source failures.

R&D Effort for Cryogenic Superconducting Magnets - Although considerable experience has been gained constructing superconducting magnets, it is crucial to perform R&D development experiments on redundant systems wherever possible to provide a fail-safe capability for the superconducting magnets.

These R&D experiments must provide a sufficient data base to permit the mean time between failures to be calculated for the superconducting magnet system.

R&D Demonstration of Reliable Space Charge-Limited Transport of a Bunched Beam - Past experiments and computer simulations have shown that transporting beams for several kilometers at their space charge limit should be possible, with little emittance growth. The key reliability issue has to do with the fluctuations that may occur in beam current from pulse to pulse. In addition the relative beam currents associated with each of the separate beams circulating in the storage rings need to be measured and equalized. In general it is necessary to demonstrate transport at high σ_0 (undepressed tune), low σ (depressed tune), continually bunching the HI beam to increase current as voltage increases.

If the HI beams have to be transported at currents lower than the space charge limit, then the accelerator will have to have a longer pulse (in the case of a single beam LINAC) or more quadrupole transport channels within the same multiple beam accelerator, thereby increasing the cost of the accelerator. The impact of this operational mode on the pulse to pulse equality of beam currents needs to be determined.

Operation of the LINAC at rather high average powers and relatively high repetition rates may affect the pulse to pulse performance of the system. This variation from pulse to pulse needs to be determined and compared with the tolerable limit on

possible beam steering once half the beams are combined in the self-focused channel. Since the clearing time in the ICF reactor precludes very high repetition rates for the D/T pellet ignition, the LINAC is forced to operate at uneconomical repetition rates. By operating the induction LINAC in the burst mode, the induction cores are used over and over, and, of course, each core is therefore smaller in diameter. The reliability of operating the LINAC in the burst mode needs to be demonstrated.

R&D Demonstrations of High Current Storage Rings for Heavy Ion Beams - The key reliability issues here have to do with demonstrating that HI beams can be reproducibly stored in rings for times typically on the order of 1 to 2 milliseconds. The reliability issues are similar to those associated with bunched beam transport, but have the additional complications associated with closed orbit synchrotrons, such as betatron and synchrotron resonances, etc., which can give rise to emittance growth, variations in beam current or outright beam loss. Furthermore, beam induced vacuum instability is another problem which must be overcome in order for long-term stability of the HI driver to be achieved. All of these issues can only be resolved with extensive experiments conducted on an experimental ring with parameters reasonably close to what is required.

R&D Experiments to Increase Metglas Reliability While Minimizing Losses - Given the fact that the Metglas is going to be located in an excoriating radiation environment, it is possible that the Metglas will gradually deteriorate until its performance is marginal or until dielectric breakdown in the Metglas begins to occur. It needs to be determined if radiation-resistant Metglas compositions are also efficient, particularly with regard to the two possible types of losses. The first type of loss in Metglas, that due to BH hysteresis losses may be intrinsic and is probably unavoidable, although further investigations into use of less hysteretic ceramic materials may be very useful. The second type is eddy current loss in the magnet cores which can be minimized by careful core design and attention to detail in proper pulse shaping of the current waveforms. The important physical parameter associated with the eddy current losses is the thickness of the Metglas ribbon and the shape and amplitude of the waveform used. Presently Metglas thicknesses of the order of 35 μ are being employed, although successful experiments have been carried out with Metglas thicknesses as small as 20 μ . By optimizing the voltage waveforms used to drive the beam and to reset the cores, the pulsed power requirements can be minimized.

Experiments and computer simulations have shown that transporting beams for several kilometers at their space charge limit should be possible, with little emittance growth. However, this HI beam transport has only been demonstrated with low energy, low power, unbunched beams. If the HI beams have to be transported at currents lower than the space charge limit, then the accelerator will have to have a longer pulse (in the case of an induction LINAC) or more quadrupole transport

channels within the same accelerator, thereby increasing the cost of the accelerator. The effect of beam current vs. HID reliability needs to be evaluated.

R&D Facility Requirements - Unique R&D facilities for both KrF laser and heavy ion driver experiments need to be provided. Since the needs of these two drivers are very different from one another, two separate facilities would be needed for reliability evaluations.

Excimer Laser Amplifier R&D Facilities - The facilities required to evaluate the reliabilities of moderate energy (4-6 kJ) excimer laser modules are relatively modest. Assuming these amplifiers were 10% efficient and operated at a pulse repetition rate of 5 Hz, power supplies of ~500 kW would suffice to power the test amplifier.

Since the KrF laser amplifier reliability is one of the key design issues to be demonstrated for these excimer laser modules, it is essential that a large number of amplifiers be tested in parallel at as high a repetition rate as reasonable. The facilities would have to be designed to accommodate automatic, 24-hour per day operation in order to permit the evaluation of mean number of amplifier firings between firings of $\sim 10^9$.

HID R&D Reliability Facility Requirements - In order to demonstrate the two key HI driver R&D issues, reliable transport of a bunched, space charge-limited HI beam and demonstration of reliable high current HI storage rings will require either the extensive modification of an existing induction LINAC or the construction of a new facility capable of meeting the HI driver requirements of transporting megajoules of energy in doubly charged, non-relativistic ~ 5 GeV lead ions. Assuming typical accelerator gradients of the order of 1 MeV/m, an accelerator having dimensions of several kilometers will be required. In addition, approximately two dozen high current storage rings having diameters of the order of 50 m will be required to investigate technologies associated with achieving the required performance levels while minimizing the cost of the storage rings.

A significant demonstration of the HI beam transport and storage ring configuration could be carried out using a single pulse, a single ring, reduced energy (to possibly 0.5 GeV), pulsed magnets, etc. Such a facility could be installed in the Advanced Test Accelerator Site 300 facility at the Lawrence Livermore National Laboratory (LLNL) at a small cost.

The requirements for the Metglas investigations are even more modest. The required R&D investigations to reduce Metglas losses can be carried out at a variety of accelerator facilities, such as those existing at the Lawrence Berkeley Laboratory (LBL), LLNL, Fermilab, Brookhaven National Laboratory, Argonne National Laboratory, etc. Support of HI indirect-drive target experiments requires a full-scale HI driver, but a HI driver that runs at a relatively low repetition rate. Thus a major facility advantage would be a significant reduction in installed power requirements since the single beam LINAC would not need to operate at 5 Hz.

Costs and Schedules

Costs of Excimer Laser Amplifier R&D - It is estimated that a minimum of \$20M and three years would be required to develop candidate excimer laser modules. Additional time and expense would be required to test the amplifiers to demonstrate 10^9 to 10^{10} firings between failures. In order to demonstrate a single beam line, it would be necessary to construct between 20 and 40 of the excimer laser modules (depending upon their output energies), together with their associated pulsed power. It is estimated that this task would cost approximately 80 M\$ once an excimer laser amplifier design had been perfected. Additional experiments and costs are described in Chapter 6.

HI R&D Reliability Experiments Cost and Schedule - The costs associated with carrying out the ambitious HI cost reduction R&D experiments are a strong function of whether or not it would be necessary to construct a new facility to meet the demanding HI driver requirements with regard to beam current, beam energy, particle energy, atomic weight of ions, etc. It is estimated that the total cost to build a conventional induction LINAC with two dozen storage rings to accomplish the R&D experiments would be of the order of \$500M. The experiments themselves would be relatively expensive if promising techniques for reducing cost required frequent rebuilding of the accelerator and storage rings. Such a facility could be constructed in five years once a suitable site had been selected. It would also be a very attractive solution to have this large HI driver facility support the related HI indirect drive target feasibility R&D experiments proposed as R&D Program #3.⁵ Significant Metglas development could continue at one or more accelerator facilities with a funding level of \$1-2M/year. Additional experiments and costs are described below in Summary of R&D Cost Estimates.

Summary of R&D Cost Estimates

**Table 5.5-9 Reliability and Lifetime for Laser Driver
R&D Task and Duration Estimates**

<u>No.</u>	<u>Task Description</u>	<u>Estimated Cost</u>	<u>Key Issue</u>	<u>R&D Duration</u>
1	Demo DD Target Beam Nesting	\$10 M	B.a.1	3 years
2	Satisfy Bandwidth Requirements	\$10 M	B.a.2	3 years
3	Laser Beam/Target Alignment System	\$12 M	A.b.1,B.a.3	4 years
4	Demo DD MJ DT Target Ignition*	\$400 M	A.a.1,B.a.1	10 years
5	Final optics pointing demo	\$5 M	A.b.1,B.a.3	3 years
6	Optics Damage Resistance Demo	\$5 M	B.a.4	3 years
7	Develop Robust GIMM	\$5 M	B.a.4	4 years
8	Develop excimer laser modules	\$20 M	B.a.2	3 years
9	Test to demonstrate 10 ⁹ lifetime	\$40 M	B.a.2	5 years
10	Demonstrate single 6 kJ beam line	\$80 M	B.a.2	4 years
11	Demonstrate 6x16=96 kJ beam line	\$120 M	B.a.2	2 years
12	Develop/Demo Laser Control System	\$40 M	B.a.2	5 years
13	Develop 50 J Raman seed generators	\$2 M	B.a.2	1 year
14	Demonstrate 6 kJ Raman converter	\$1 M	B.a.2	1 year
15	Demo 100 kJ Raman converter	\$20 M	B.a.2	2 years
16	Develop programmable SBS chirper	\$2 M	B.a.5	1 year
17	Subscale SBS PC demonstration	\$2 M	B.a.5	1 year
18	Develop Large Aperture SBS chirper	\$10 M	B.a.5	3 years
19	Demo 6 kJ SBS Pulse Compressor	\$5 M	B.a.5	2 years
20	Demonstrate 100 kJ PC	\$20 M	B.a.5	3 years
21	Dev.Large Aperture Fast Pockels Cells	\$20 M	B.a.5	5 years
Total Laser Driver R&D Costs		\$829M		

*Includes cost of Nova Upgrade.

**Table 5.5-10 Reliability and Lifetime for Heavy Ion Driver
R&D Task and Duration Estimates**

<u>No.</u>	<u>Task Description</u>	<u>Estimated Cost</u>	<u>Key Issue</u>	<u>R&D Duration</u>
1	Demo Single Accel. in Burst Mode	\$15 M	B.b.1	3 years
2	Develop Bright Pb ⁺² Source	\$10 M	B.b.1	3 years
3	Develop high brightness HI injector	\$20 M	B.b.1	2 years
4	Demo low emittance through injector	\$10 M	B.b.1	2 years
5	SP HI Pulse Synch. and Timing Demo	\$10 M	B.b.1	3 years
6	SP Triplet Focusing Demo	\$10 M	B.b.2	2 years
7	SP HI Channel Formation Demo	\$100 M	B.b.2	7 years
8	SP Injection of HI Beam in Channel	\$10 M	B.b.3	3 years
9	SP Demo of Channel Transport @ MA	\$50 M	B.b.3	5 years
10	SP HI Beam Stripping	\$20 M	B.b.4	2 years
11	SP HI Neutralization	\$5 M	B.b.4	1 year
12	Develop high PRF burst-mode pwr.sup.	\$30 M	B.b.3	2 years
13	Demo superconducting quadrupoles	\$20 M	B.b.3	3 years
14	Demo storage ring performance	\$50 M	B.b.3	3 years
15	Demo bunchers	\$25 M	B.b.3	3 years
16	Develop HID Computer Control System	\$20 M	B.b.5	5 years
17	Alignment of HI Beam to ID Target	\$400 M	B.b.5	10 years
Total Heavy Ion R&D Costs		\$805M		

References for 5.5.3.7

1. Gary J. Linford at TRW/ATD and Dan Driemeyer MDA, "R&D for Critical Issue #6: Demonstration of High Overall Laser System Efficiency," January 1992.
2. "New Techniques for KrF Laser Fusion Systems," Interim Report for Los Alamos National Laboratory, pp. 2-70 through 2-72, Los Alamos, New Mexico, written by Dr. Mark Kushner, then at Spectra Technology, Inc., Seattle, Washington (1986).
3. V. Yu. Baranov, et al., "Use of a Discharge over a Dielectric Surface for Pre-ionization in Excimer Lasers," Sov. J. Quantum Electron., 11, pp. 42-45 (1981).
4. V. Yu. Baranov, et al., "UV-Preionized Rare Gas Halide Lasers with Plasma Electrodes," Proceedings of the International Conference on Lasers 1981, pp. 968-974 (1981).
5. V. V. Apollonov, et al., "High Power Molecular Lasers Pumped by a Volume Self-Sustained Discharge," J. Opt. Soc. Am. B, 8, pp. 220-229, (1991).
6. Alfred Maschke, Gary Linford, and Steven Fornaca, "R&D for Critical Issue #5: Cost Reduction for the Heavy Ion Driver," TRW S&TG/ATD, January 1992.

5.5.3.8 R&D for Demonstration of Non-Linear Optical Laser Driver Architecture

(Relevant Key Issues: B.a.1, B.a.2, B.a.3, B.a.4, B.a.5.)

Description of Problem - As discussed in both Critical Issue #6 and #14,^{1,2} the MDA inertial fusion energy (IFE) reactor design study (IFERDS) excimer laser non-linear optical (NLO) architecture is made up of NLO components which can be tailored to permit safe, efficient, and versatile operation of the laser driver.

The MDA Team Inertial Fusion Energy Reactor Design Study NLO architecture consists of two major devices:

- (1) The Raman accumulators (used for beam combination in the crossed Raman [or CRAM configuration])
- (2) The SBS pulse compressors

Although there are still NLO R&D issues to be settled, the physics of both the Raman accumulators and the SBS pulse compressors is well understood. R&D work relevant to specific key issues associated with the Prometheus laser driver described here include:

- B.a.1 DT Target Illumination Issues,
- B.a.2 Large Laser Development and Bandwidth Issues,
- B.a.3 Final Optics Pointing System,
- B.a.4 Grazing Incidence Mirror Damage,
- B.a.5 SBS Pulse Compressor,

R&D CRAM Accumulator Problems - A key to achieving high efficiency with Raman accumulators is to start with a design that exhibits a high quantum efficiency, ξ , together with a large Raman gain coefficient, g_R . Stimulated rotational Raman gain in H_2 (or D_2) has been previously investigated and promises to fulfill the requirements for both ξ and g_R . Since the Raman accumulators are also expected to be operated in the CRAM configuration (to improve the beam quality of the output Stokes beam), some inefficiencies arise. The Raman accumulators need to be driven with a synchronized Stokes seed having appropriate temporal and spectral components. The major R&D problems are to demonstrate:

- (a) Efficient beam combination
- (b) Achievement of high beam quality
- (c) Suppression of higher order Stokes orders from being generated
- (d) Pump intensity averaging
- (e) Suppression of parasitic oscillations

Secondary Raman accumulator problems have to do with details associated with efficient generation of synchronized Stokes seeds which are correlated³ with the excimer pump beams.

R&D Problems Associated with the Stimulated Brillouin Pulse Compressor - When the stimulated Brillouin scattering (SBS) process is applied to the problem of temporally compressing long (>250 ns) excimer/Raman accumulator laser pulses, the SBS process tends to produce subnanosecond pulses⁴ with high efficiencies (> 95%). When a longer pulse (such as the 6 ns main pulse specified by the TWG)⁵ is required, the needed compressed pulse length can be generated by a ramped-Stokes seeded SBS cell, but at considerable cost of overall efficiency. Since the sum of the energies of the compressed 6 ns pulse and the long undepleted (>250 ns) pulse is approximately 100% of the original long excimer/Raman accumulator pulse, the overall efficiency of the ramped-Stokes seeded SBS cell can be improved by utilizing the long, undepleted pump pulse as the long precursor pulse to the target (as specified by the TWG).⁵ The following operational details need to be demonstrated in an R&D program:

- (1) Demonstration of the performance (efficiency, pulse shape versatility, etc.) of a ramped Stokes seeded SBS cell.
- (2) Control over competing processes, parasitic oscillations, multi-order Stokes, etc.

- (3) Demonstration of the use of an electro-optical switchyard, pulse delay lines, etc., for utilizing depleted pump as the precursor pulse.
- (4) Performance of electro-optical "chirper" SBS Stokes seed generators.

Description of Required R&D Efforts

CRAM Accumulator R&D - The R&D program for the CRAM Raman accumulator is relatively simple and straightforward. It builds upon the extensive work already completed. Two types of Raman accumulator systems need to be addressed: single pulse and high repetition rate.

Single Pulse CRAM Accumulator R&D

The following single pulse CRAM R&D accumulator tasks need to be addressed:

- (1) Demonstration of efficient (> 80%) rotational CRAM conversion in H₂ (or D₂)
- (2) Demonstration of an effective (correlated) rotational CRAM Stokes seed generator
- (3) Demonstration of excimer pump beam intensity averaging and beam quality enhancement for CRAM accumulator geometries
- (4) Coherent, large aperture beam synthesis
- (5) Control of diffraction and egg-crate damage by image relay optics.

Although some of these R&D tasks can be demonstrated at sub-scale energies, the most convincing single pulse Raman accumulator R&D plan would involve a full, 100 kJ beamline.

High Repetition Rate CRAM Accumulator R&D - These CRAM R&D experiments need to deal primarily with the gas circulation problems to remove the phonon heat from the H₂ (or D₂) gas without adversely affecting the accumulator beam quality.

SBS Pulse Compressor R&D - In a manner analogous to the Raman accumulator described above in CRAM Accumulator R&D, the SBS pulse compressor R&D experiments need to be divided between single pulse proof-of-principle experiments and high average power experiments dealing with control of thermal effects.

Single Shot SBS Pulse Compressor R&D - Both sub-scale and full scale single shot R&D SBS pulse compressor experiments need to be performed. The fundamental working principles of the SBS pulse compressor can be demonstrated in sub-scale experiments. These sub-scale experiments involve full scale physical lengths of the SBS cell ($L_{\text{cell}} = c\tau_{\text{pump}}/2$) but, to reduce costs, subapertures of perhaps 1/20 full aperture may be employed. These subscale SBS R&D experiments would include the following tasks:

- (1) Demonstration of high pulse compression conversion efficiency using a self-seeded, "chirped" input Stokes SBS seed.⁶
- (2) Demonstration of versatile SBS pulse compressor output pulse shapes by using a ramped "chirped" Stokes SBS seed.
- (3) Demonstration of the operating principles of an electro-optical "switchyard" involving fast Pockels cells to tailor the undepleted pump pulse into an 80 ns long precursor pulse.

These experiments could be carried out at convenient apertures (~5 cm) using pulse energies of 250 J and 250 ns durations

In order to conduct the full scale SBS Pulse Compressor R&D experiments, it would be necessary to have large aperture pump beams containing ~100 kJ. The MDA SBS Pulse Compressor design features a relatively large aperture, ~1 m. Although this large 1 m aperture can be synthesized from an array of smaller optics supported in an "egg-crate" structure. These full scale experiments would be similar to the sub-scale experiments with the additional feature that transverse SBS parasitics could be investigated as a potential problem.

High Average Power SBS Pulse Compressor R&D Experiments - As described above for the single shot SBS pulse compressor R&D experiments, both subaperture and full aperture high average power R&D experiments can be performed. Since the primary purpose of the high average power experiments is to investigate the influence of phonon-induced thermal effects in the SF₆-filled SBS cell, it is very likely that only subaperture high average power experiments would produce meaningful results for the relative costs.

Facility Requirements

Raman Accumulator R&D Facilities - The single shot subscale Raman accumulator R&D experiments can be performed with modest laboratory facilities.

The high average power Raman accumulator R&D experiments would require significant input powers from excimer pump amplifiers. If an entire single beam of the laser driver were to be tested, an input energy/pulse of approximately 100 kJ would be required, possibly in the form of either 25 (5x5) 4 kJ excimer laser modules or 16 (4x4) 5.5 kJ excimer laser modules. These experiments could be combined with tests of test excimer laser amplifiers to realize significant cost savings. The full scale Raman accumulators would have apertures of ~1 m and gain lengths of the order of 10 m.

SBS Pulse Compressor R&D Facilities - The single pulse, subaperture SBS pulse compressor R&D facilities can be performed in a modest laser facility having a long optical path (~50 m) available. For a square 5 cm aperture SBS cell pumped with a

Raman accumulator pulse of duration 250 ns and energy of 250 J, a cell length of approximately 38 m would be required.

Full aperture, high average power SBS compressor R&D facilities are similar to those described above for the high average power Raman accumulator experiments with the additional requirement that sufficient laboratory space be provided for the 38-m long SBS pulse compressor cells.

Cost and Schedule

Cost of CRAM Accumulator R&D Experiments - Single pulse, subscale Raman accumulator R&D experiments can be performed for ~\$2 M. High repetition rate subscale Raman experiments would cost \$7M. Combined with the construction of an array of NxN excimer amplifiers described in Section 4.1, above, a full aperture 1x1 m CRAM accumulator could be tested for an additional \$20M for a total of \$100M (NxN excimer amplifiers + Raman accumulator). This would take an estimated five years from beginning to end.

Additional experiments and costs are described below in Summary of R&D Cost Estimates.

Cost of SBS Pulse Compressor R&D Experiments - The subaperture single SBS pulse compressor experiments could be carried out for \$4M over a two-year period. Full aperture, high average power tests of a full scale SBS pulse compressor could be carried out in association with construction of a NxN excimer laser pump array in (CRAM Accumulator R&D Experiments) and a full aperture, high average power Raman accumulator (SBS Pulse Compressor R&D Experiments) for an additional \$20M for a total cost of \$120M (\$80M for the excimer lasers, \$20M for the Raman experiments, and \$20M for the SBS experiments). This is estimated to take eight years from beginning to end. Additional experiments and costs are described below in Summary of R&D Cost Estimates.

Cost of Computer Control and Alignment R&D Experiments - It is recommended that these R&D experiments be conducted subscale with the predominant emphasis on testing the target tracking and alignment system. This task is estimated to cost \$20M in conjunction with a full scale DT target launching system. Additional experiments and costs are described below in Summary of R&D Cost Estimates.

Summary of R&D Cost Estimates

**Table 5.5-11 Demonstration of Non-Linear Optical Laser Driver
R&D Task and Duration Estimates**

<u>No.</u>	<u>Task Description</u>	<u>Estimated Cost</u>	<u>Key Issue</u>	<u>R&D Duration</u>
1	Satisfy Bandwidth Requirements	\$10 M	B.a.2	3 years
2	Laser Beam/Target Alignment System	\$12 M	A.b.1, B.a.3	4 years
3	Final optics pointing demo	\$5 M	A.b.1, B.a.3	3 years
4	Optics Damage Resistance Demo	\$5 M	B.a.4	3 years
5	Develop excimer laser modules	\$20 M	B.a.2	3 years
6	Test to demonstrate 10 ⁹ lifetime	\$40 M	B.a.2	5 years
7	Demonstrate single 6 kJ beam line	\$80 M	B.a.2	4 years
8	Demonstrate 6x16=96 kJ beam line	\$120 M	B.a.2	2 years
9	Develop/Demo Laser Control System	\$40 M	B.a.2	5 years
10	Develop 50 J Raman seed generators	\$2 M	B.a.2	1 year
11	Demonstrate 6 kJ Raman converter	\$1 M	B.a.2	1 year
12	Demo 100 kJ Raman converter	\$20 M	B.a.2	2 years
13	Develop programmable SBS chirper	\$2 M	B.a.5	1 year
14	Subscale SBS PC demonstration	\$2 M	B.a.5	1 year
15	Develop Large Aperture SBS chirper	\$10 M	B.a.5	3 years
16	Demo 6 kJ SBS Pulse Compressor	\$5 M	B.a.5	2 years
17	Demonstrate 100 kJ PC	\$20 M	B.a.5	3 years
18	Dev. Large Aperture Fast Pockels Cells	\$20 M	B.a.5	5 years
Total Laser Driver R&D Costs		<u>\$414M</u>		

References for 5.5.3.8

1. Gary J. Linford, "ICFRDS Critical Issue #6: Demonstration of High Overall Laser System Efficiency," TRW S&TG/ATD, December 1991.
2. Gary J. Linford, "ICFRDS Critical Issue #14: Demonstration of Non-Linear Optical Laser Driver Architecture," TRW S&TG/ATD and Dan Driemeyer, MDA, December 1991.
3. "Final Report of the Raman Beam Combining Program," Shirley J. Pfeifer, et al., TRW E&DS, Redondo Beach, CA, and Northrop Research & Technology Center, Palos Verdes Peninsula, CA, Contract # F29601-85-c-0053 (September 1986) submitted to the Air Force Weapons Laboratory, AFSC, Kirtland Air Force Base, NM 87117.
4. "New Techniques for KrF Laser Fusion Systems," Interim Report for Los Alamos National Laboratory, pp. 2-70 through 2-72, Los Alamos, New Mexico, written by Dr. Mark Kushner then at Spectra Technology, Inc., Seattle, Washington (1986).

5. "Inertial Confinement Fusion Reactor Design Studies Recommended Guidelines," Ronald C. Davidson (MIT) et al., prepared for the Department of Energy Office of Fusion Energy, Germantown, MD (September 1990).
6. "Optical Methods for Laser Beam Control," Artur A. Mak and Leonid N. Soms, Proceedings of SPIE, 1415, Modeling and Simulation of Laser Systems II, pp. 110-119 (1991).

5.5.4 R&D for the Cavity - This section contains the R&D for the cavity. This includes (1) first wall protection, (2) blanket, and (3) shield.

5.5.4.1 R&D Needs for First Wall Protection - A basic test plan for the first wall protection system has been devised, in which a number of parallel near-term tests are performed on separate or multiple issues, followed by a facility in which integrated cavity responses are simulated. Figure 5.5-1 shows a possible scenario for this test plan.

Near-term R&D tasks are best classified by the types of facilities required. The tasks areas include:

- A. Film flow
- B. Vapor behavior
- C. Component structural responses
- D. Material interactions
- E. Blast simulation

Facility requirements can be very different for the different tests. Blast simulation is a treated as a separate R&D task even though it is not an issue itself. The ability to perform useful engineering testing prior to construction of an IFE fusion reactor depends greatly on the quality of the blast simulation available.

Following 10-15 years of separate and multiple effects testing, there is a strong need to construct a test facility which combines all of the interrelated factors which impact the feasibility of the cavity concept. Uncertainties in cavity behavior can not be resolved without combining film thermal hydraulics, vapor dynamics and structural responses.

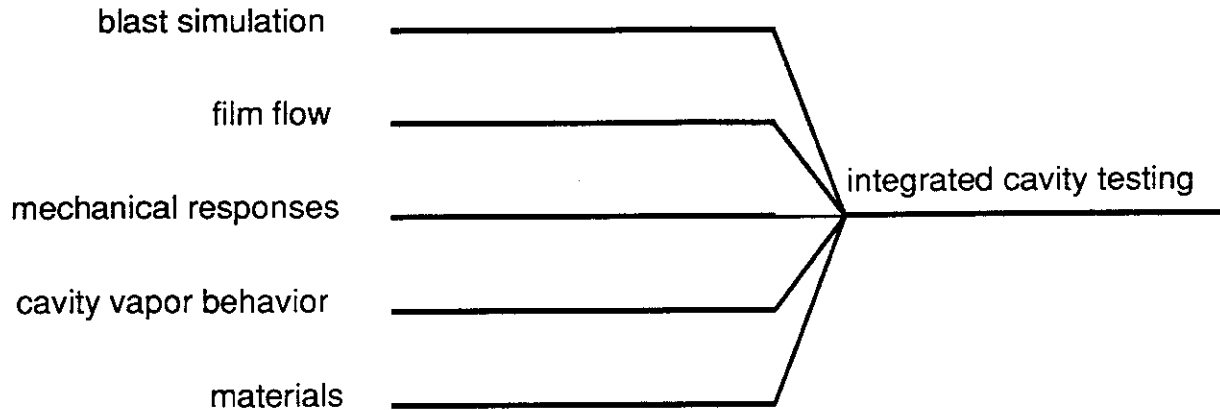


Figure 5.5-1. Testing Logic for the First Wall Protection System

A. Film Flow

Issue #E.a.5. Film flow control: injection, uniform thickness, and drainage

Issue #E.a.6. Film flow stability and response to impulsive loading

Description: Film flow is currently an active research area. Hydrodynamic behavior of films on vertical and curved surfaces is not fully-understood, particularly under the environmental conditions imposed on the Prometheus first wall. In addition, the unique materials and flow paths add uncertainties. In order to resolve issues related to film flow, both experiments and modeling are needed.

These experiments should demonstrate that adequate wall coverage can be attained to prevent first wall structure damage. This includes studies of film stability, development of effective injection and drainage systems, and film thickness control studies. Some specialized tests are needed. For example, the concept of MHD guiding to protect inverted surfaces should be explored. Transient response in the porous wall also requires study.

An active modeling effort will be very useful for this R&D task. There are many possible geometric configurations and component designs. Experimental data alone will validate a single design, but will be difficult to extrapolate to other designs.

Facility Requirements: These issues are grouped together because they can be addressed under a similar set of environmental conditions. Except for the issue of blast effects on film stability, blast simulation is not critical. Many tests can be performed without heating as well. The most important condition to simulate is flow geometry.

Several small-scale facilities can be envisioned. These would be devoted to separate flow issues, such as flow control, injector development, etc. The facilities would consist of a flow loop with process control and loop heaters. Test sections would be installed into the loops and tested. Combining these tests into a single loop facility may reduce costs, although the equipment costs in these tests are minimal. At least one small facility should have the capability to simulate blast pressure effects.

Cost and Time: A possible test plan involves four subtasks, as listed below. Time to perform the tests and cost estimates are also given. Sequential testing leads to a total test time of ~10 years.

Table 5.5-12 First Wall Protection R&D Task and Duration Estimates

<u>R&D Task</u>	<u>Time Required</u>	<u>Facility Cost</u>	<u>Yearly Operating Cost</u>
Film thickness control	3 yrs.	\$200k	\$100k
Flow on inverted surfaces	3 yrs.	\$200k	\$100k
Flow around obstructions	3 yrs.	\$200k	\$100k
Transient flow through porous structures	2 yrs.	\$200k	\$100k
Stability tests	5 yrs.	\$500k	\$200k
Injector development	5 yrs.	\$2-5M	\$1M

B. Cavity Vapor Response to Blast and Clearing Demonstration

- Issue #E.a.1. Cavity vapor hydrodynamics
- Issue #E.a.3. Vapor condensation rate
- Issue #E.a.4. Radiation heat transport in partially-ionized gas

Description: Some models exist to predict the cavity vapor response to the blast (sometimes referred to as the "fireball"). The response includes blast energy deposition, vapor hydrodynamics and mass transport, thermal radiation, and evaporation/recondensation processes. Almost no experimental verification is available, such that confidence in the predictions is very low. Even if the models are accurate for idealized conditions, there are many potential non-ideal effects which could occur, and which are very difficult to accommodate in the models without empirical data. As data becomes available, more effort can be placed on model improvement.

A key to successful testing is to simulate the energy release characteristics from the target explosion. Without this, the responses may bear little resemblance to a real reactor. The experiments should measure the major responses, including time-dependent temperature, pressure, and heat and mass fluxes to the surface. Ideally,

one would measure spatial variations in these parameters. The tests should demonstrate that the time to clear the cavity allows for high repetition rates in a reactor.

Facility Requirements: The major facility for this R&D task consists of a relatively large cavity which represents the wall protection scheme to be tested and simulates the blast energy sources. Surface heating and bulk heating of the cavity vapor are most important, but bulk heating of the surface would be useful to simulate isochoric heating effects.

Since heat transfer to the coolant is a small source of uncertainty, the most important region to simulate is the surface facing the explosions. This surface should use prototypic materials, configurations and environmental conditions. The size of the cavity depends on the blast simulation. In principle, the most important conditions to simulate involve local intensity, and not the total yields. Rapid pulsing may not be required, but would help identify any cumulative effects due to multiple blasts.

Smaller experiments can be devised to address specific aspects of this issue; however, it is unclear how the source term could be reproduced in a small experiment. These might include small, focused tests of shock propagation, vapor condensation, radiation cooling rates and transport in partially ionized Pb, and specialized tests to explore non-ideal effects (multi-dimensional effects, droplet formation & behavior, etc.)

Cost and Time: - The larger integrated facility would be of the order of \$10-20M to construct and \$1-2M per year to operate.

- (1) Separate-effects tests (e.g., shock propagation, vapor condensation, radiation transport and cooling rates, multi-dimensional effects, droplet formation and behavior) are expected to cost ~\$100-200k each with annual operating budgets of the order of \$100k. Assuming ten such tests, the total is \$1.5M+\$1M per year.
- (2) A single multiple-effects cavity vapor test facility is estimated to cost \$1-2M with annual operating cost of \$250k.

The total time to complete this task is 10-15 years.

C. Cavity Structure Mechanical Response to Blast

Issue #E.a.2. Cavity structure mechanical response to blast

Description: The response to highly-transient loading in complex, engineered structures (i.e., SiC composites with Pb infiltration) is very uncertain. This issue is important to establish the survivability and lifetime of the solid structures which absorb the blast. Some useful information on failure modes will also be obtained. Assuming

the material properties, such as fatigue lifetime, are well-characterized, the tests do not necessarily have to be performed up to end-of-life. Tests must measure stress and strain in the structures, and run to enough cycles to identify major problem areas. Locations where stresses are highest should be more highly instrumented to ensure the design limits are not exceeded anywhere in the structures.

The structure geometry should be as close to prototypic as possible, including the mechanical support system. Scaling of the tests may be possible, but ultimately a full scale experiment should be performed. First wall panels in Prometheus are modular, such that even the full-scale tests would be only ~2 m x 2 m. The most important environmental condition to simulate is the pressure loading at the front of the wall. Methods to obtain prototypic impulsive loading without fusion explosions should be explored.

Facility Requirements: A range of tests is suggested, from specimen to large-scale tests. The pressure loading can be simulated with a combination of radiant heat deposited in a very short pulse, together with a gas shock. For the more integrated tests, a cavity is required to simulate the multiple shock waves that reflect off of the structures. More sophisticated sources may be needed. Source development is similar to the R&D task described above, except that rapid, continuous pulsing is more important in order to provide adequate cycles.

Cost and Time: A possible test plan involves 4 steps, as listed below. Time to perform the tests and cost estimates are also given. Sequential testing leads to a total test time of 10 years.

<u>R&D Task</u>	<u>Time Required</u>	<u>Facility Cost</u>	<u>Yearly Operating Cost</u>
Sub-scale tests	5 yrs.	\$200k	\$100k
Scale-model prototypes	5 yrs.	\$1M	\$500k
Panel tests	5 yrs.	\$2M	\$1M

D1. Pb/SiC Wettability

Issue #E.a.7. Pb/SiC Wettability

Description: Pb and SiC do not wet naturally. Poor wetting could render the wetted wall concept impractical. Surface modifications to the SiC (such as CVD impregnation with a metal) may provide a wettable surface. Tests should be conducted to determine methods to provide wetting (including fabrication issues), measure the contact angle, and study capillary behavior in porous materials.

Facility Requirements: Most of these tests can be performed without major new facilities.

Cost and Time:

	<u>Test Time</u>	<u>Operating Cost</u>
Fabrication	1-2 years	\$250k/yr
Property measurements	2 years	\$250k/yr
Capillary flow tests	2 years	\$250k/yr

D2. Pb Compatibility with Steel

Issue #E.a.8. Pb Compatibility with Steel

Description: Corrosion of steel by Pb is not well-characterized. In Prometheus, the maximum first wall coolant temperature is determined, in part, by compatibility of Pb with the steel in the heat transport system. These tests should establish supportable temperature limits and explore methods to enhance the compatibility of Pb and steels. This might involve impurity control systems or modifications to the bulk or surface of the steel.

Facility Requirements: Two types of tests are considered: specimen and loop tests. Loop tests can be forced or natural convection. Facility needs are modest in either case. Flow loops are needed with heating and cooling capabilities. Post-test examination has the most demanding facility requirements, but several existing facilities are available.

Cost and Time:

	<u>Equipment</u>	<u>Operating</u>	<u>Test Time</u>
Specimen tests	\$100k	\$100k/yr	2 years
Loop tests	\$500k	\$250k/yr	3-5 years

E. Blast Simulation Development

Description: Due to the difficulties of using real pellet explosions as the source term, alternate methods of obtaining a good simulation of fusion explosions must be developed.

F. Partially Integrated Cavity Test Facility (Issues E.a.1-6)

Description: Film flow, cavity hydrodynamics, cavity clearing, and mechanical responses can and should be studied in separate facilities; however, the phenomena present in the cavity are highly interrelated. For example, proper loading conditions on the film and wall structures requires the presence of prototypical hydrodynamics. Cavity clearing depends to a large extent on the film thermal hydraulics. Many large uncertainties will remain until a cavity mock-up test is performed with all of the essential features present.

The ability to simulate the energy deposition from the blast is a critical issue for this facility. If appropriate non-nuclear pulsed energy sources are not feasible, then it may be necessary to perform these engineering tests in a nuclear facility with high-power drivers, targets, etc. The cost of such a facility may be quite high. A separate R&D program will be needed to develop alternative blast simulations. There is a need for both single-shot and repetitively-pulsed tests.

Facility Requirements: There is not sufficient information available to know the degree to which these tests can be scaled. As a minimum, cavities of 1-2 m in diameter will be required. Using prototypical surface power densities, at least 20-40 MW of pulsed power will be needed. A full coolant and film supply system is needed, as well as complete vacuum and impurity control system.

Cost and Time: This facility is a major element in the cavity R&D program. It integrates results from a large number of separate effects tests, and contains all of the necessary subsystems to validate acceptable cavity responses and clearing time.

The cavity or at least parts of it should be replaceable. These test component replacement costs are included in the operating budget. Cost estimates are as follows:

<u>Equipment</u>	<u>Operating</u>	<u>Test Time</u>
\$50M	\$5M/yr	10 yrs

5.5.4.2 R&D Needs for the Blanket - The blanket R&D needs for IFE solid breeder blankets are very similar to those for MFE solid breeder blankets since the

issues are the same. Reference 1 covers in reasonable details such needs. Here, only a brief description of the important uncertainties and R&D needs is given.

The most important uncertainties in the list of issues for solid breeder blankets relate to tritium breeding, tritium recovery, and breeder thermomechanical behavior. These are particularly large because: (1) there is limited understanding of gas transport in irradiated solids, (2) designs must keep the low thermal conductivity solid breeders within their respective temperature limits under substantial nuclear heating and neutron damage rates, and (3) the resulting designs have a significant amount of non-breeding structure and coolant. The primary safety uncertainties are associated with the behavior of the blanket under off-normal or transient conditions and to the control of tritium under normal conditions.

A coordinated program is needed to address the uncertainties associated with the solid breeder blanket issues. First a material development and characterization program is required. A series of single-effect or partially integrated types of experiments are then required to test either individual or group of issues. Finally, more integrated submodule-size experiments would address several issues. The write-up below gives a brief description of the major tasks required for such a program, following the above classification and listing in each case the solid breeder blanket issues being addressed.

Reference for 5.5.4.2

1. M. A. Abdou, et al., "Technical Issues and requirements of Experiments and Facilities for Fusion Nuclear Technology – FINESSE Phase 1 Report," PPG-909, UCLA-ENG-85-39, University of California, Los Angeles, December 1985.

Material Development and Characterization

(All Issues)

Description: The development of an attractive blanket depends strongly on the development of attractive solid breeder and structural materials. Material development refers to the process of identifying possible classes of materials, understanding the effects of material parameters, such as its microstructure and impurity content, and characterizing the material through measurement of its properties. This task is most effective when done early in the program, and has already been carried out for several years.

The most important needs are:

- (1) Measurement of basic properties, such as thermal conductivity of different material forms, swelling and thermal stability, and characterization of the material microstructure. For the solid breeders, other measurements of particular interest include tritium diffusion parameters and tritium surface adsorption/desorption activation energies, while for the SiC composite of interest, tritium permeation needs to be fully characterized.
- (2) Fabrication of different material forms, in particular sintered pellet and sphere pac forms for the solid breeders, and tube sheet form for the SiC composite.
- (3) Understanding of the importance of the effect of various material parameters on the material properties.

Facility: No major new facility is required.

Cost and Time: The cost is about \$12M/yr over about five years.

Neutronics and Tritium Breeding

Issue #E.b.1. Tritium self-sufficiency

Issue #E.b.9. Heat generation and power production

Description: Uncertainties here range from nuclear cross-section uncertainties to the heating profiles in the blanket and achievable tritium breeding ratio. The required tasks include measurement of the neutron spectra and reaction rates (tritium, heating, transmutations) under progressively more relevant blanket geometries to provide for verification of basic nuclear data, data libraries and neutronics analysis techniques. A well-calibrated 14-MeV neutron source is required. Point neutron source measurements have been made, and recently line source experiments have been initiated.

Facility: Existing 14-MeV neutron source facility, such as the one at JAERI, exist and are being used to address these issues. Verification of tritium self-sufficiency would require a fusion facility.

Cost and Time: The program consists of experiments on simple geometry for about three years, followed by experiments on blanket mock-ups for about three years. The capital cost for the test assembly is about \$10M for the simple geometry and about \$15M for the blanket mock up. The operating cost in both case is about \$3M/yr.

Issue #E.b.2. Tritium Inventory and Recovery

Description: Predicting tritium behavior in solid breeder blankets requires understanding tritium transport, retention and chemical form in the breeder material under the influence of the fusion environment. Transport processes include intragranular diffusion, grain boundary diffusion, surface processes, diffusion through

interconnected porosity, and convection by the purge flow. Tritium retention processes include solubility, surface adsorption, and chemical and radiation trapping. The tritium behavior is influenced by many factors, such as temperature, purge gas composition and burnup.

A program of experiments and modeling studies is underway to address this issue. The experiments include:

- (1) Laboratory experiments to characterize the microstructure and measure transport and surface properties of lithium ceramics, such as temperature controlled desorption experiments. These experiments are part of the material development and characterization task described above. The effort should be expanded in this area to provide better fundamental data for modeling application, in particular for the surface mechanism activation energies.
- (2) Closed capsule experiments in fission reactors followed by controlled anneals in laboratories to address internal grain transport, surface desorption and trapping; some experiments also focus on single crystal specimens in which bulk diffusion tends to be particularly important and from which a better estimate of the diffusive properties of the materials can be obtained.
- (3) In-situ tritium recovery experiments which consist of open, actively purged test capsule irradiated in a fission reactor. These tests explore the tritium behavior over a range of parameters, including temperature, temperature gradient, material characteristic, burnup, sweep gas composition and purge flow rate. Advanced in-situ tests would also include the partially integrated effects, such as breeder/clad interaction.

Over the last few years, a vigorous modeling effort has also been carried out in parallel and complementary to the experimental program, resulting in much progress in the understanding of tritium transport mechanisms and in the interpretation of experimental data. The effort needs to be pursued and to concentrate on mechanisms still poorly understood, such as dissolution and chemical and irradiation trapping.

Facility: No major new facility is required, since these experiments are carried out in existing fission reactors.

Cost and Time: Most of the tests are ongoing, except for advanced in-situ tests (which could be part of a more integrated nuclear submodule test). Efforts are still required to better characterize fundamental tritium transport mechanisms, in particular surface fluxes, and irradiation and chemical trapping. In parallel, a vigorous modeling effort should continue to help better understand, interpret and apply the results to blanket situations.

The cost estimates are about \$15M for the capital cost of test assemblies, and about \$8M/yr as overall operating costs over eight years.

Blanket Thermomechanical Behavior

Issue #E.b.3. Breeder/structure mechanical interactions

Issue #E.b.6. Corrosion and mass transfer

Description: The R&D needs in this category include investigation of breeder-structure thermomechanical behavior, heat transfer and corrosion/mass transfer, in particular the determination of operating temperature limits. Earlier experiments are underway and include laboratory corrosion test of unirradiated material in particular to investigate Li_2O mass transfer at temperature. Small-scale experiments to observe the thermal performance of a breeder/clad/coolant unit cell are also required in conjunction with irradiated capsule test to observe the irradiation effect on the breeder/clad thermomechanical interaction. These irradiated tests can be carried in fission reactors, and the more integrated test could use the same test assembly as that for the advanced in-situ test.

Facility: No major new facility is required, since these experiments are carried out in existing fission reactors or in laboratory facilities.

Cost and Time: Some tests are ongoing. Future efforts should address the thermo-mechanical interaction and corrosion characteristics of solid breeder and SiC.

The cost estimates are about \$3M for the capital cost of test assemblies, and about \$3M/yr as overall operating costs over 5 years.

Non-Neutron Module Test

Issue #E.b.3. Breeder/structure mechanical interactions

Issue #E.b.4. Off-normal and accident conditions

Issue #E.b.5. Structural response and failure modes

Issue #E.b.6. Corrosion and mass transfer

Issue #E.b.7. Tritium permeation

Issue #E.b.8. Fabrication & Assembly

Description: Nuclear testing is critical for exploring the effects of radiation on issues such as tritium recovery and breeder/structure mechanical behavior over the lifetime of the blanket. However, fission reactor test facilities provide limited test space, and also

impose constraints on the type and severity of transient tests, which limits the test information that can be obtained.

A complementary non-neutron experiment would provide valuable and needed information on prototypical-size integrated modules under near-prototypical conditions (except for irradiation effects) if suitable heat sources can be identified. Such a facility could address all the issues listed above. For example, it could provide for:

- (1) Fabrication of a prototypical-size module or even segment if required which would help demonstrate fabrication and assembly techniques for a blanket module.
- (2) Thermomechanical test of the blanket module under normal operation, including demonstration of thermal behavior over different power levels and flow conditions, which would help develop design margins.
- (3) Thermalhydraulic test of purge flow, as well as test of permeation to the coolant within the blanket by using deuterium or hydrogen added to the purge. Control of the purge flow composition would also allow for observation of any corrosion or material interaction for different gas chemistry (at least over a short time).
- (4) Off-normal and severe transient tests (which could be done at the end of the test program with the particular module) including LOCA and LOFA conditions. Structural response and failure mode could also be addressed at the end based on off-normal conditions and/or pressurization.

In addition, a modeling effort is required in order to develop design codes for the thermomechanical behavior of solid breeder blankets. Such a facility would then provide a discriminating test for these design codes.

Facility: A major new facility would be required. It would need to be able to house at least a full-size blanket module (of the order of 1m x 1m x 1m) and to provide for over power and severe transient testing, such as pressurization test. Heat sources to simulate the nuclear heat generation and coolant and purge flow systems would be required. Test module instrumentation would include strain gauges and thermocouples.

Cost and Time: The capital cost is estimated at about \$20M for the facility, and about \$15M for fabrication of a module, and the operating cost at \$3M/yr. Testing in this facility would follow the initial single and multiple-effect types of experiments and would last about four years.

Nuclear Submodule Test

- Issue #E.b.2. Tritium inventory and recovery
- Issue #E.b.3. Breeder/structure mechanical interactions
- Issue #E.b.5. Structural response and failure modes
- Issue #E.b.6. Corrosion and mass transfer
- Issue #E.b.8. Fabrication & Assembly

Description: Such a submodule test would be carried out in a fission reactor. Size constraint would mean that only part of a module assembly could be tested. However, a test submodule would comprise solid breeder, clad, purge and coolant in a prototypical arrangement under near-prototypical operating conditions, including the key effect of irradiation. This would be the most integrated test under irradiation with prototypical temperatures, flow rates and purge chemistry, and would provide key information, particularly on tritium recovery and breeder/clad interaction including corrosion. Parameters such as the submodule interface with the reactor and the solid breeder enrichment would be chosen in function of the facility to try to reproduce prototypical tritium generation and nuclear heating rate profiles.

The test would also provide for small-scale fabrication of part of a module assembly and PIE tests would provide valuable information on tritium inventories as well as on structural material conditions following operation at near-prototypical conditions, including irradiation.

Results would also help to validate design models, in particular for tritium recovery and inventory.

Facility: No major new facility is required, since this experiment will be carried out in existing fission reactors. The choice of fission reactor will depend on a number of parameters, such as available test space and ability to reproduce nuclear heating and tritium production rates over time.

Cost and Time: This test would start approximately at the same time as the non-neutron module test and will last about seven years per submodule.

The capital cost for a test submodule fabrication is about \$15M, and the operating cost is about \$3M/yr.

5.5.4.3 R&D Needs for Shielding

Effectiveness of Bulk Shield

- Issues: #E.c.1.1 Biological Dose During Operation and After Shutdown for Maintenance.
#E.c.1.2 Radiation Streaming.
#E.c.1.3 Analytical Techniques and Data Base.

Description: Integral experiments should be planned to resolve the above technical issues associated with the effectiveness of the bulk shield. The prediction accuracies of calculated occupational dose, neutron and gamma flux level outside the biological shield, and the safety factors impeded in the design to account for higher flux level around gaps/slits due to neutron streaming through these paths or through larger penetrations (e.g. vacuum ducts) are estimated based on comparing predicted values to experimental measurements.

An intense 14-MeV neutron source with intensities $>10^{13}$ n/s and continuous operation capability should be used. Experiments should be conducted first to characterize the boundary conditions and background levels prior to the shielding performance experiments. The size of the mock-ups should be 100-150 cm wide and 80-150 cm long. The material constituents of the mock-ups could be conventional (316SS, water and concrete) or innovative materials that have superior attenuation capabilities (SiC+Pb+B₄C+water.) Arrangements can be in homogeneous or heterogeneous set-ups. Figures 5.5-2 through 5.5-6 show examples of possible configurations that also include discontinuities and penetrations. Measured parameters are: (a) Neutron spectrum ($E_n > 2$ MeV, 1 keV $< E_n < 1$ MeV), (b) Gamma spectrum, (c) Dose equivalent behind shield, and (d) Gamma heating during and after irradiation.

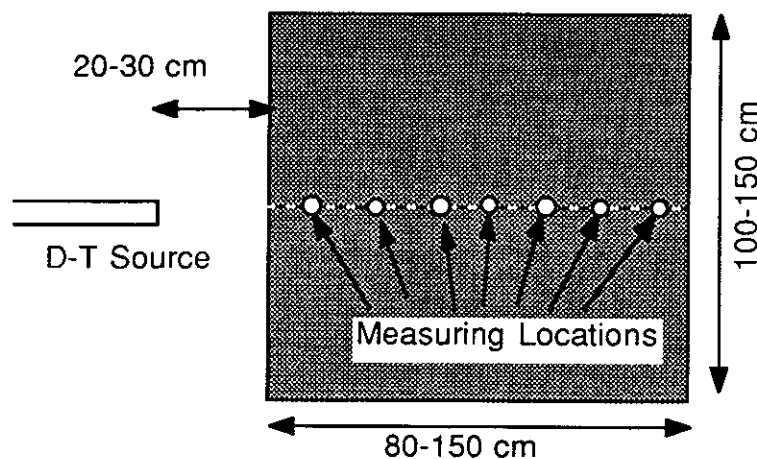


Figure 5.5-2. Example Bulk Shield Test Assembly – Homogeneous Assembly

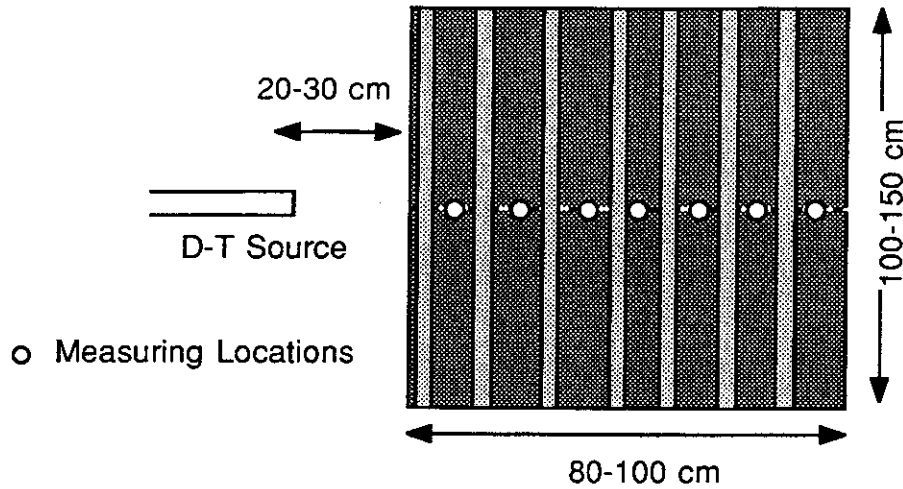


Figure 5.5-3. Example Bulk Shield Test Assembly – Heterogeneous Assembly

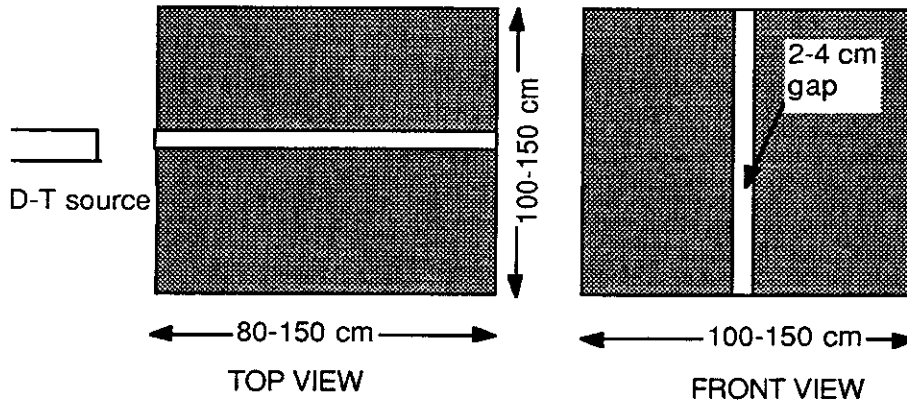


Figure 5.5-4. Example Bulk Shield Test Assembly With Discontinuities and Penetrations – Straight Plane Gap Assembly

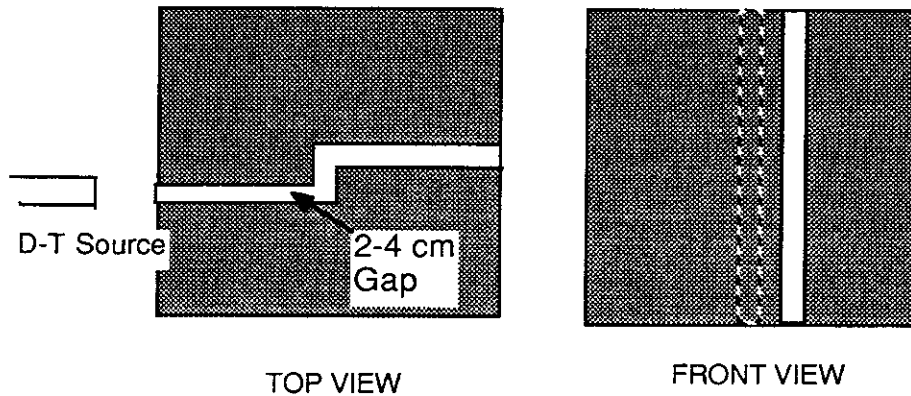


Figure 5.5-5. Example Bulk Shield Test Assembly With Discontinuities and Penetrations – Stepped Plane Gap Assembly

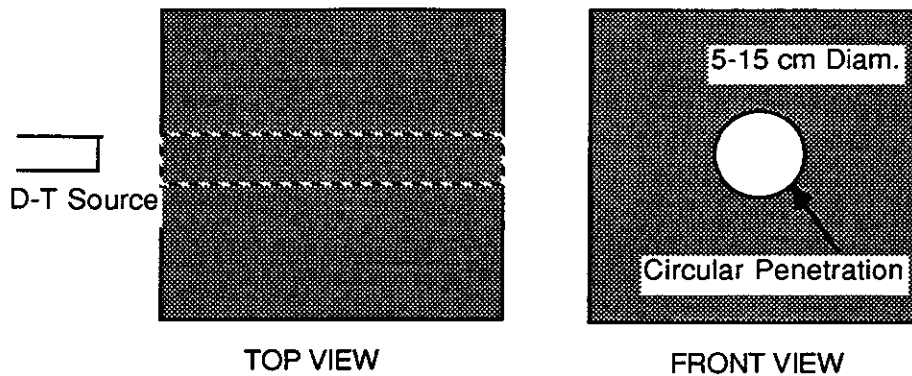


Figure 5.5-6. Example Bulk Shield Test Assembly With Discontinuities and Penetrations - Assembly With Circular (or Rectangular) Duct

Facility: An Intense 14-MeV neutron source is required to perform the above integral experiments. One of the U.S. facilities should be upgraded or reactivated. It is estimated that \$1.5M is required to bring the ORNL 14-MeV shield facility to full operation while meeting the most current operational safety standards. However, this facility has 14-MeV neutron source intensity of only 10^9 n/s. For an intensity of 10^{13} n/s or higher, it is estimated that an additional \$2M is needed. A new facility similar to the Japanese FNS facility with a similar intensity capability will cost ~\$15-20M.

Cost and Time: It is estimated that ~\$800k/year operating cost is required to perform a series of experiments for the validation of the bulk shield effectiveness (including penetrations experiments.) Operating cost include machine operation, test assembly materials and construction, and manpower. It is estimated that for each experiment, the manpower is ~8 man-months including operators, maintenance personnel, experimentalists and analysts. A 4-5 year period is required to accomplish this R&D task.

Shielding of Sensitive Components

- Issues: # E.c.4 Shielding of final and turning mirrors (L)
 # E.c.5 Shielding of quadrupole magnets (HI)

Description: Damage to the final mirrors in a laser reactors is mainly caused by prolonged bombardment by high-energy neutrons causing displacements of the atoms of materials constituting these mirrors in addition to excessive heating that leads to thermal deformation and reduced performance. In a HI reactor, the superconducting quadrupole magnets are damaged by the radiation dose deposited in the insulator, displacements to the Cu stabilizer atoms leading to increase resistivity, etc. The R&D required to resolve these issues are two fold: (a) Experimental/theoretical validation of the microstructural changes that materials undergo under irradiation which lead to performance degradation, and (b) accuracies involved in quantifying (estimating) the

irradiation source term responsible for these microstructural changes. The former is a material life-time issue and is covered under the R&D requirements for materials (ISSUE E.) while the latter is related to the validation of the computational tools and data base required to quantify the nuclear environment at these sensitive components and behind the shield installed to protect these components.

An intense 14-MeV neutron source with intensities $>10^{14}$ n/s and continuous operation capability should be used in integral experiments devoted to resolve the shielding issues of (b) above. Experiments should be conducted first to characterize the boundary conditions and background levels prior to the shielding performance experiments. The configurations of these experiments are characterized by the implementation of a long penetration of a typical length of 10-20 m. The penetration could have a bend to resemble the laser (or some of the beamlets) paths in IFE reactors. A zone that has a highly neutron absorbing material could be located behind the bending to simulate the neutron trap situated at the back of the final mirrors in laser reactors. Due to the necessity of using long penetration in this class of integral experiments, the neutron source strength should be higher than 10^{14} n/s in order to achieve good statistics on the measurements performed at the far end of the penetration.

The surrounding shield material around this penetration could be made of conventional shielding materials (316SS+water; concrete) or innovative materials that have superior attenuation capabilities (SiC+Pb+B₄C+water). Measured parameters are: (a) Neutron spectrum ($E_n > 2$ MeV, 1 keV $< E_n < 1$ MeV), (b) Integrated fast neutron fluence ($E_n > 0.1$ MeV), (c) Gamma spectrum, and (d) Gamma heating. Figure 5.5-7 shows possible configurations relevant to these integral experiments. The validation of the prediction accuracies for these parameters at locations near and outside the outer surface of the test assembly is necessary in quantifying the level of confidence in calculating the damage parameters to the quadrupole magnets in HI reactors. Comparing calculated parameters to measurements near and behind the bend will indicate the prediction accuracies in assessing the damage to the final grazing incident mirrors in laser reactors. Performing measurements near the end of penetration will also assess the prediction accuracies of the nuclear environment at the turning mirrors in these reactors.

Facility: A very high intensity 14-MeV neutron source is required to perform the above integral experiments. For an intensity of 10^{14} n/s or higher, it is estimated that a new facility similar to the Japanese FNS facility with the capability of 10^{12} n/s intensity will cost ~\$20-25 M.

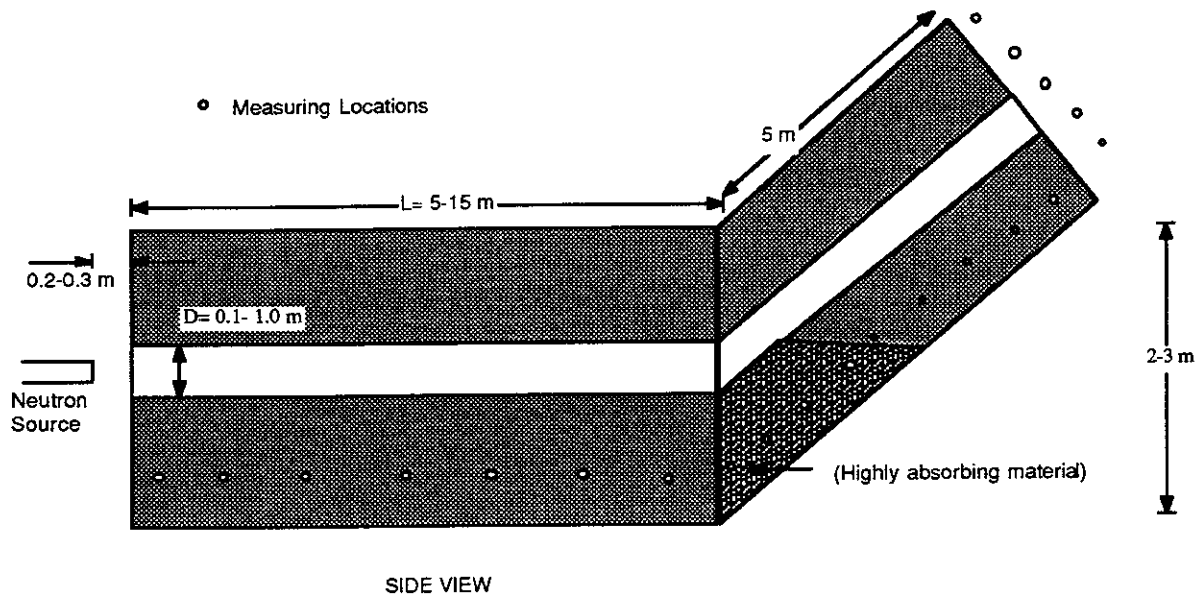


Figure 5.5-7. Proposed Configuration for Test Module for Verification of Mirror Protection and Quadrupole Magnet Protection Scheme

Cost And Time: It is estimated that ~\$1-1.5M/year operating cost is required to perform a series of experiments that utilizes a relatively long test assembly composed of different shielding materials surrounding the penetration. Operating cost include machine operation, test assembly materials and construction, and manpower. It is estimated that for each experiment, the manpower is ~10 man-months including operators, maintenance personnel, experimentalists and analysts. two-three year period is required to accomplish this R&D task.

5.5.5 R&D for Tritium System - There are six major topics which should be included in the fuel cycle R&D program to achieve the objective of a practicable operating fusion plant.

- (1) Demonstrate an advance fuel impurity treatment process - high temperature isotope exchange.
- (2) Demonstrate a ceramic breeder tritium recovery process that allows extraction from a helium purge without oxidation - pressure swing adsorption.
- (3) Demonstrate low inventory hydrogen isotope separation by cryogenic distillation.
- (4) Demonstrate extended operation of integrated test loops with tritium.
- (5) Develop and demonstrate the purification of the first wall protectant liquid lead with acceptable tritium inventories and losses.
- (6) Demonstrate processing of solid, liquid and gaseous waste streams.

Facilities - The R&D plan assumes the use of current facilities (with modifications) where possible. All development and testing R&D could be accomplished in existing and under-construction tritium facilities in the U.S., Canada and Europe.

Prototype processing loops are planned to be tested in separate facilities. An integrated test stand of prototype processes would be assembled and demonstrated in a single, large facility.

Schedule - To demonstrate removal of tritium from impurity waste streams by high temperature isotope exchange (1995).

To demonstrate a process to remove tritium from helium purge gas from solid breeders (1997).

Demonstration scale test of new CD column concept to reduce tritium inventory (1997).

Demonstration scale test of waste processing (1997).

Integrated test loop demonstration (2000).

R&D Costs - The estimated R&D costs for the tritium system are \$15M capital expenditure for facilities and \$1.5M per year operating costs with a program duration of about ten years.

5.5.6 Safety and Environment - Many of the issues and R&D discussed for various reactor components relate to safety and environmental considerations. Some additional R&D specific to safety and environment is discussed in this subsection.

5.5.6.1 Overall Plant Tritium Inventory (Issue J.1) - See description of R&D requirements for Key Issue D.1.

5.5.6.2 Permeation of Tritium (Issue J.2)

Description - In order to resolve this issue, both the transport of tritium into the liquified lead and the retention of tritium by the lead must be understood. A program of experiments and modeling that would allow for these processes to be understood includes:

- Laboratory experiments to characterize the adsorption of tritium into liquid lead as a function of pressure and temperature.
- Laboratory experiments to characterize the desorption of tritium from the lead through the wall of the heat exchanger material as a function of pressure and temperature.
- The adsorption of tritium by sodium must also be studied via laboratory experiments, as a function of pressure and temperature.

Facility - A heat transfer laboratory which can handle tritium is needed to perform these experiments. Existing tritium experimental facilities may be suitable for this purpose.

<u>Cost & Time</u> -	With existing facility:	\$250,000
	Without existing facility:	TBD
	Time period:	Within five years

5.5.6.3 Normal Operation Tritium Release (Issue J.3) - See description of R&D requirements for Key Issue 5.5.6.2.

5.5.6.4 Neutronic Cross Sections/Data Library for Activation Analysis (Issue J.4)

Description - Computational tools and data libraries used for activation analysis in the fusion community can be verified through decay rate measurements in a simulated fusion neutron spectra. Such validation has been initiated at UCLA for W and Zr. For example, the Prometheus study identified a large uncertainty in the $O^{17}(n,\alpha)$ cross section which results in about two orders of magnitude difference in the C^{14} production and radioactivity. Such uncertainty is critical as it has large impact on classification of waste disposal from the Li_2O breeder. However, extensive experimental and theoretical investigations are still needed. The R&D requirements with regards to the activation issue are common to both MFE and IFE.

Decay rate measurements can be done by examination of specimens following irradiation and removal from the irradiation facility. The tests would measure the decay gamma spectrum and count rate. Verification procedures include: (1) identification of decay photon spectra of the irradiated sample; (2) experimental decay rate calculations; (3) computer code simulation; and (4) comparisons of calculated and measured values and search for sources of discrepancies.

Facility Requirements - A facility with a fusion-like neutron spectrum is needed for the experiments. Such an environment can be generated by using 14 MeV neutrons (produced from a deuterium beam impinging on a tritiated target) surrounded by an assembly of materials in a configuration that simulates the fusion environment. In general, this type of facility is used for tritium generation and neutron cross section measurement. Existing facilities includes FNS facility in JAERI and others.

Cost and Time - A new facility similar to the FNS with neutron source intensity of 10^{12} n/s will cost ~\$15M. It is estimated that for each experiment, the average manpower is about 3 man-months including irradiation, data analysis and validation of computational tools. The total program would last 5 years with annual operating cost of \$600K.

5.5.6.5 Removing Decay Heat from Lead Coolant Under Accident Conditions (Issue J.5)

Description - Failure to cool the radioactive lead following a coolant spill might result in a local structure damage and releases to the environment. These tests seek to measure and locate the radioactive lead coolant under cooling break conditions. Research for this area includes the development of remote lead activity monitoring and remote lead cleanup system. In addition, verification tests of after-heat level would help assuring that adequate cooling is available.

Test Facility - A fluid loop with pressurizer, piping, pump, valve, break joints and any other components is desirable to simulate the lead coolant spreading behavior under a loss of coolant accident condition. The coolant and environmental pressures should be preserved and the size of test space should be large. The simulations should cover different break sizes and break locations. Decay heat measurement can be addressed in the same facility for decay rate measurements.

Cost and Time - It is estimated that the cost of the fluid loop is of the order of \$500K. The task might take 1 year for planning, design and construction, with an additional year for performing experiments and data acquisition. The annular operating cost could be of the order of \$300K.

5.5.6.6 Hydrogen Burn Due to Rupture of Diffusion Vessel

Description - Rather than experimental research, an engineering analysis is required to resolve this issue. This analysis would use existing methodology to calculate the effects of a hydrogen burn, and develop a design which would be able to sustain such an accident. Parameters which would be studied include: (a) the initial amount of hydrogen/tritium present, (b) the initial pressure and temperature within the diffusion vessel, (c) the rate of release of hydrogen/tritium from the diffusion vessel, (d) the amount of oxygen available. Existing computer programs which could be utilized include HECTOR and CONTAIN.

Facility - None

<u>Cost & Time</u> -	Cost:	\$50,000
	Time period:	within six months

5.5.6.7 Detection of Local Dry Spots Prior to Failure (Issue J.7)

Description - These tests consist of the investigation of dry spot creation mechanism of FW, development of in-situ detection and repair techniques and development of radiation heat transport modeling capability in a partially-ionized gas environment.

Tests which address the formation of local dry spots on the first wall include the neutron irradiation effect on the porous SiC structure, structure degradation due to interactions with unburned pellet and deposition of corrosion product.

Experimental and modeling efforts of radiation heat transport in partially-ionized gas are covered under the R&D requirements for cavity vapor behavior. Estimation of time to failure for a local dry spot is about 19 minutes for a wall thickness of 0.5 cm. The above calculation assumed a local thermodynamic equilibrium condition for the cavity gas. Further analysis should consider the effects of non-thermodynamic equilibrium, gas excitation and self-shielding on the gas conditions.

Test Facility - Transport and deposition of corrosion product on SiC porous FW can be studied using a fluid loop with or without neutron sources. (Neutron yields neutron bulk heating which provides better simulation of coolant bulk temperature). The fluid loop consists of a vertical portion of SiC porous tube for creation of the film flow, with the rest of the loop made from stainless steel to simulate the heat transport loop. Measurements include coolant temperature, impurity content, and standard post-test examination of surfaces for corrosion. Experiments of irradiation effects on SiC structure require a fusion-like neutron spectra environment and are covered under the R&D requirements for materials.

A full size module might be needed to simulate the accessibility for tests related to in-situ repair technique development.

Cost and Time - It is estimated that the cost of the fluid loop facility without neutron source is of the order of \$500K. The amount of time required for this task includes one year for design and construction, with an additional year for performing experiments, data acquisition and post test examination. The operating cost is of the order of \$300K per year.

5.5.6.8 Detailed Accident Analysis (Issue J.8)

Description - In order to resolve this issue, detailed accident scenarios must be developed for each of the identified initiating events for each system in the plant. A more completely developed design is necessary for the development of the accident scenarios. Once the scenarios have been developed, the detailed accident engineering analysis would be initiated. During the accident analysis it is expected that various data/information will be identified as being required to complete the analysis, but is unavailable. Specific R&D needs to provide these data/information would evolve as the engineering accident analysis evolves.

Facility - None is required for the detailed accident engineering analysis to be performed.

The facilities required to resolve this issue depend on what data/information is identified during the detailed accident engineering analysis.

Cost & Time - Detailed accident engineering analysis:

Cost: \$1M (5 man-years)
Time period: 2 years

5.5.6.9 Removal of Contaminants from the Liquid Lead (Issue J.9)

Description - The tritium aspects of this issue are addressed in Key Issue 5.5.6.2. The first step to resolve this issue is to identify which are the potential contaminants and their expected amounts. Once this has been done, both the transport of contaminants into the liquid lead and the retention of contaminants by the lead must be understood. A program of experiments and modeling that would allow for these processes to be understood includes:

- Laboratory experiments to characterize the adsorption of contaminants into liquid lead as a function of pressure and temperature.
- Laboratory experiments to characterize the desorption of contaminants from the lead through the wall of the heat exchanger material as a function of pressure and temperature.
- The adsorption of contaminants by sodium must also be studied via laboratory experiments, as a function of pressure and temperature.

Facility - A heat transfer laboratory is need to perform these experiments. Such a laboratory may already exist (e.g., university, national laboratory).

Cost & Time - With existing facility: \$1M
 Without existing facility: TBD
 Time period: Within five years

5.5.6.10 Impact of Large Quantities of Lead on Waste Disposal (Issue J.10)

Description - This is a regulatory issue to be resolved by the NRC.