GA Technologies

UCRL--15885

DE87 008727

Final Report

**INNOVATIVE APPROACHES TO
INERTIAL CONFINEMENT
FUSION REACTORS**

by
**ROBERT F. BOURQUE
KENNETH R. SCHULTZ
and PROJECT STAFF**

Work supported by
**Lawrence Livermore National Laboratory
Subcontract 8214905 under
Department of Energy Contract No. W-7405-ENG-48**

**GA PROJECT 3434
NOVEMBER 1986**

MASTER

ABSTRACT

This final report covers three separate topics investigated by GA Technologies for Lawrence Livermore National Laboratory under the same contract. All are in the general area of innovative approaches to inertial confinement fusion (ICF) reactor design. First, issues pertaining to the Cascade reactor concept are discussed. Then, several innovative concepts are presented which attempt to directly recover the blast energy from a fusion target. Finally, the Turbostar concept for direct recovery of that energy is evaluated.

The Cascade issues discussed are combustion of the carbon granules in the event of air ingress, the use of alternate granule materials, and the effect of changes in carbon flow on details of the heat exchanger. Carbon combustion turns out to be a minor problem. Four ICF innovative concepts were considered: a turbine with ablating surfaces, a liquid piston system, a wave generator, and a resonating pump. In the final analysis, none show any real promise. The Turbostar concept of direct recovery is a very interesting idea and appeared technically viable. However, it shows no efficiency gain or any decrease in capital cost compared to reactors with conventional thermal conversion systems. Attempts to improve it by placing a close-in lithium sphere around the target to increase gas generation increased efficiency only slightly.

It is concluded that these direct conversion techniques require thermalization of the X-ray and debris energy, and are Carnot limited. They therefore offer no advantage over existing and proposed methods of thermal energy conversion or direct electrical conversion.

CONTENTS

ABSTRACT	iii
1. INTRODUCTION AND SUMMARY	1-1
1.1. INTRODUCTION	1-1
1.2. CASCADE ISSUES	1-2
1.3. ICF INNOVATIVE CONCEPTS	1-3
1.4. TURBOSTAR	1-5
1.5. OTHER POSSIBILITIES	1-11
1.6. CONCLUSIONS	1-13
2. CASCADE ISSUES	2-1
2.1. CARBON SURFACE LAYER COMBUSTION	2-1
2.1.1. Background	2-1
2.1.2. Approach	2-2
2.1.3. Results	2-3
2.2. ALTERNATE GRANULE MATERIALS	2-4
2.2.1. Beryllium Surface Layer	2-4
2.2.2. Silicon Carbide/Lithium Oxide Blanket	2-6
2.3. EFFECT OF REDUCED CARBON FLOW RATE	2-8
2.4. ELABORATION OF CASCADE COST ACCOUNTS	2-10
3. ICF INNOVATIVE CONCEPTS PROGRAM	3-1
3.1. OBJECTIVE AND SCOPE	3-1
3.2. ABLATION TURBINE	3-2
3.2.1. General Principles	3-2

3.2.2. Multiaxis Ablation Turbine	3-6
3.2.3. Conclusion	3-11
3.3. LIQUID PISTON	3-11
3.4. WAVE GENERATOR	3-16
3.5. RESONANT PUMP	3-16
3.6. SUMMARY	3-20
4. TURBOSTAR	4-1
4.1. DESCRIPTION OF TURBOSTAR CONCEPT	4-1
4.2. BASIC POWER FLOWS	4-2
4.3. ANALYSIS OF CLOSE-IN LITHIUM SPHERE	4-6
4.4. EFFECT OF PULSATING FLOW ON TURBINE	4-19
4.5. POWER BALANCES	4-22
4.5.1. Turbostar with Bare Target	4-23
4.5.2. Turbostar with Li-Sphere	4-24
4.5.3. Turbine System with Mass Injection	4-24
4.5.4. Comparison with Thermal Cycle	4-26
4.5.5. Summary	4-28
4.6. OTHER CONSIDERATIONS	4-31
4.7. CONCLUSIONS	4-32
5. OTHER POSSIBILITIES	5-1
6. SUMMARY AND CONCLUSIONS	6-1
6.1. CASCADE ISSUES	6-1
6.2. ICF INNOVATIVE CONCEPTS	6-2
6.3. TURBOSTAR	6-3
6.4. CONCLUSIONS	6-3
7. REFERENCES	7-1

FIGURES

1-1. Multiaxis ablation turbine schematic	1-5
1-2. Liquid piston concept	1-6
1-3. Turbostar concept proposed by LLNL	1-7
1-4. Nuclear heating profiles in lithium sphere for two fusion energy levels. 200 and 2000 MJ	1-8
1-5. Cumulative fraction of energy in gas ball, showing effect of total fusion energy	1-9
1-6. Net conversion efficiencies for Turbostar case with lithium sphere sized for complete vaporization	1-10
1-7. Summary of power balance results for two Turbostar configurations, a direct turbine injection system, and a thermal system	1-11
1-8. Multiple liquid lithium reactor with bottom axis	1-12
2-1. The Cascade reactor concept	2-2
2-2. Heat line for SiC/Li ₂ O blanket option	2-7
2-3. Heat exchanger heat line for carbon granule flow	2-9
2-4. Original carbon granule heat exchanger drawn to scale	2-10
3-1. Original concept for the ablation turbine	3-3
3-2. Blowoff velocity diagram	3-4
3-3. Multiaxis ablation turbine schematic	3-7
3-4. Multiaxis turbine	3-8
3-5. Ablation turbine with blowoff bouncing off opposite blades	3-9
3-6. Blade efficiency for ablation turbine for one to four elastic bounces and for inelastic (sticking) case	3-12
3-7. Liquid piston system operational sequences	3-14
3-8. Ratio of work out for a given expansion ratio to that for an infinite expansion ratio for diatomic ($k=1.4$) and monatomic ($k=1.67$) gases	3-15
3-9. Wave generator concept	3-17
3-10. Resonant pump concept	3-18

3-11. Inertial boost pump that served as basis for the resonant pump concept . . .	3-19
4-1. Original Turbostar concept proposed by LLNL	4-3
4-2. Alternate Turbostar embodiment	4-4
4-3. Turbostar power flow schematic	4-6
4-4. Close-in room temperature lithium sphere with cylindrical insert and target chilled to 20 K	4-8
4-5. Spherical deposition profiles for lithium and lithium-lead normalized to incident flux at r_0	4-10
4-6. Energy line for lithium at solid density	4-11
4-7. Nuclear heating profiles in lithium sphere for two fusion energy levels, 200 and 2000 MJ	4-12
4-8. Radius to saturated vapor in lithium sphere as a function of fusion energy yield	4-13
4-9. Average energy, temperature, and pressure in lithium gas ball as a function of fusion yield	4-14
4-10. Cumulative fraction of energy in gas ball, showing effect of total fusion energy	4-15
4-11. Work out for isentropic ideal gas expansion for two gases	4-16
4-12. Net conversion efficiencies for Turbostar case with lithium sphere sized out to saturated vapor	4-18
4-13. Radiation loss rate from 13 cm lithium gas ball assuming gas is perfect conductor	4-19
4-14. Nozzle and blade arrangement and velocity diagram for impulse turbine	4-20
4-15. Effect on turbine efficiency of gas velocity variation ignoring viscous and turbulence losses	4-22
4-16. Turbostar with bare target and thermal bottoming cycle	4-23
4-17. Turbostar with close-in lithium sphere and with thermal bottoming cycle	4-25
4-18. Enthalpy - entropy diagram for lithium vapor showing possible adiabatic expansions through a turbine	4-27

- 4-19. Enthalpy – entropy diagram for sodium vapor showing possible
adiabatic expansions through a turbine 4-28
- v 4-20. Power flow for direct turbine injection 4-29
- 4-21. Power flow for simple lithium fall and thermal conversion system 4-29
- 4-22. Summary of power balance results for two Turbostar configurations,
a direct turbine injection system, and a simple thermal system 4-30
- 5-1. Upward flowing lithium fall reactor 5-2
- 5-2. Multipass liquid lithium reactor with horizontal axis 5-3
- 5-3. Active hot well to direct lithium flow and pressure-balanced heat
exchangers 5-5
- 5-4. The Field cycle 5-6

TABLES

- 2-1. Detailed resolution of cost discrepancies between Cascade (GA) and MDAC 2-12
- 5-1. Some field cycle specs 5-7

1. INTRODUCTION AND SUMMARY

This report presents the results of the technical work performed during 1986 on the ICF Innovative Concepts Project for the Lawrence Livermore National Laboratory Inertial Fusion Program.

1.1. INTRODUCTION

This project was primarily an investigation of departures from the traditional methods of converting fusion power to electricity, where the high energy fusion products are thermalized and directed toward a blanket/first wall coolant, for example, helium or liquid lithium. Either coolant can transfer its heat to a conventional steam cycle or the helium can be used directly in a Brayton cycle. In any case, high pressures are required at high temperature, which is a difficult engineering combination.

Capital costs are also an issue. Conventional steam cycles are expensive and not particularly efficient. It therefore seemed worth exploring direct energy recovery methods that could be more efficient and cheaper.

While exploration of direct energy recovery concepts constituted the main task of this project, some time was spent clearing up loose ends in the recently completed Cascade ICF Reactor Design Study^[1-1&1-2]

Key results are summarized in this section. The Cascade issues are reported in Section 2. Innovative direct energy recovery concepts are discussed in Section 3. A direct recovery concept originated at LLNL called Turbostar^[1-3] is analysed in Section 4. Section 5 discusses an alternate reactor embodiment to the Hylife reactor studied by LLNL.^[1-4]

1.2. CASCADE ISSUES

The Cascade issues addressed were (1) possible combustion of the carbon surface granule layer, (2) exploration of alternate granule materials, and (3) the effect of reducing the carbon surface layer mass flow rate, and (4) cost estimates. The last consists of minor changes that allow as much of the reactor plant as possible has been costed as non-nuclear grade because of the low activity inherent in the Cascade design.

A. Carbon Combustion. Combustion of Cascade's carbon granule surface layer could occur in the event of accidental air leak into the reactor chamber. At issue is whether or not radioactive lithium aluminate, the primary radioactive species in the blanket, would be released to the environment. Release could occur through ejection of solid particles due to pressure buildup or through vaporization of the lithium aluminate. Neither is likely to occur. Any pressure buildup would be vented through the same leak that admitted the air. Because combustion products would tend to block further combustion, pressure rise would be slow. Temperatures would never reach the boiling point of the lithium aluminate. In fact, the adiabatic flame temperature would probably not reach the melting point of lithium aluminate of 2200 K. Heat generated by combustion could be removed by the heat exchangers provided they remained intact. If they failed, the vented helium would purge out the air and put out the fire.

B. Alternate Granules. We explored two alternate granule combinations: a beryllium surface layer with a lithium aluminate blanket, and a silicon carbide/lithium oxide system. With a beryllium surface layer, any vapor would quickly recondense on cooler Be granules. Because the reaction to gaseous BeO is endothermic, air combustion does not occur spontaneously. Because of thermal stress limitations, however, Be metal can take only 1/25 the energy dose as carbon. Hence, Be metal does not appear to be a viable substitute to carbon.

The SiC/Li₂O option is appealing because of its low activity, low vapor pressure of its dissociation products (1.0 torr for silicon at 2300 K, for example), and high thermal stress capability of SiC. Power conversion efficiency should be about the same as the reference

Cascade design but the heat exchangers would be about twice the size, primarily because of the lower temperature of the Li_2O . This would cause about a five percent increase in total capital cost, which may well be offset by the cost savings stemming from the lower activity. The disadvantage with SiC or any other compound is that it will dissociate into its constituents which, in all probability, will condense separately. The question, then, is whether or not one should start off with these dissociated products.

C. Surface Layer Flow Reduction. With the original C/BeO/LiAlO₂ Cascade blanket, we examined the effect of reducing the carbon surface layer flow rate from 2.2 m³/sec to 1.0. Two cancelling effects occur: (1) the carbon heat exchanger area increase 53%, and (2) because of this increase, the helium pumping power for this heat exchanger decreases about a factor of two. This frees up an additional 10.6 MW(e) for sale so that the cost of electricity drops slightly despite the increase in capital cost.

D. Cascade Costing. The final Cascade issue examined was the cost accounting for the Cascade reactor plant. Because of the low activity and inherent safety, many of the reactor plant systems can be non-nuclear grade, with substantial cost reduction. The Cascade costing was independently reviewed by MacDonnell-Douglas Astronautics Co. (MDAC) as part of a separate review project.^[1-4] In section 2.4, we discuss the details of this cost analysis.

1.3. ICF INNOVATIVE CONCEPTS

The purpose of this task was to explore ways of directly recovering the non-neutron energy from an ICF target explosion. This energy comprises 35-40% of the total, and, as will be discussed, addition of a close-in lithium sphere can increase it further. There is considerable incentive to exploit this directed energy in a non-thermal way to see if it leads to higher efficiencies.

Because existing thermal systems can recovery 45% of the fusion energy and advanced systems closer to 55%, we used the criteria of 70% total conversion efficiency (direct plus bottoming cycle) or significant cost reduction at nominal efficiency when evaluating the

concepts. In addition to the Turbostar concept discussed later, we examined four concepts conceived by GA Technologies Inc. :

1. Ablation turbine,
2. Liquid piston,
3. Wave generator, and
4. Resonant pump.

A. Ablation Turbine. The idea behind the ablation turbine was to use the non-neutron energy to vaporize a small amount of continuously replenished material from the surface of turbines blades. This eventually evolved into the multiaxis ablation turbine concept shown in Fig. 1-1. Analysis had shown that coupling efficiency was very poor unless either the blowoff thickness was of the same order as the blade thickness remaining or the blowoff was allowed to bounce back and forth between blades depositing more impulse each time. Neither turned out to be true. Blowoff thicknesses calculated by LLNL were orders of magnitude smaller than any reasonable blade thickness so that energy coupling efficiency was near zero. And while multiple bouncing might increase energy coupling if the blowoff were a solid, in fact the gaseous blowoff would quickly fill the chamber and randomize. In short, there was no realistic scenario where reasonable conversion efficiencies could be expected, so this concept was therefore abandoned.

B. Liquid Piston. The liquid piston concept was an attempt to use vaporized lithium near the target to drive the remaining liquid lithium through a hydraulic turbine. The sequence of operations is shown schematically in Fig. 1-2. It employs a wetted wall, several rapid closures, and a suction valve to create the initial void space for pellet injection. While potentially quite efficient, it would be far too bulky and slow to be practical. A variation on this is the more compact Turbostar concept discussed later.

C. Wave Generator. This was an idea to exploit the wave action that would take place in a rotating column of liquid metal after a target explosion. Unfortunately, the amount of energy available in a wave, even with very high artificial gravity due to rotation, is small compared to the energy generated. Therefore, this concept was also quickly discarded.

FIG. 1-1. Multiaxis ablation turbine schematic.

D. Resonant Pump. This concept was an attempt to use a resonating system to build up the energy level from a series of target explosions so that energy could be effectively extracted. It turns out that each pellet explosion is quite massive, equivalent to 19's of kg of TNT, hardly in need of multiplication. Also, the internal energy of a resonating system is not available for extraction. If attempted, the resonance decays. Therefore, like the others, this concept was dropped.

1.4. TURBOSTAR

The Turbostar concept for direct recovery of the non-neutron energy was suggested by LLNL.^[1-3] It is shown conceptually in Fig. 1-3. It resembles a turbine equivalent of the liquid piston concept discussed above. A liquid lithium fall is accelerated radially by the target X-ray and debris energy. The resulting kinetic energy is withdrawn by a hydraulic turbine. Residual thermal energy is extracted by a thermal bottoming cycle.

FIG. 1-2. Liquid piston concept.

In order to maximize the advantage of this concept, we explored means of increasing the fraction of fusion energy that goes into kinetic energy of the fall. Accordingly, we examined the effect of surrounding the target with a lithium sphere sized such that all of

FIG. 1-3. Turbostar concept proposed by LLNL.

it would be vaporized by the pellet explosion. The resulting gas ball would free-expand isothermally to a manageable pressure and then accelerate the lithium fall. Before firing, most of the sphere would initially be at room temperature. There would also be a cylindri-

cal insert at 20 K containing the target that would be inserted into the sphere just before firing. Thermal expansion would cause the two pieces to lock together. The energy cost of refrigerating the insert would be negligible.

The nuclear heating profiles in a lithium sphere are shown in Fig. 1-4 for two fusion energy yields. Deposition is very steep and a large fraction of the fusion energy goes into high temperature gas. This is shown in Fig. 1-5. Depending on fusion yield, between 55 and 75% of the fusion energy can go into forming the gas ball. Note that, to achieve the higher values, fusion yields must be on the order of several tons TNT equivalent.

FIG. 1-4. Nuclear heating profiles in lithium sphere for two fusion energy levels, 200 and 2000 MJ.

While a fairly large fraction of the fusion yield can be converted to photon and debris energy, not all of it can be converted into fall kinetic energy and extracted by the turbine.

FIG. 1-5. Cumulative fraction of energy in gas ball, showing effect of total fusion energy.

Fig. 1-6 shows net efficiencies defined as turbine work out to fusion energy in. Compared to the gas fractions shown in Fig. 1-5, it is seen that about half of the gas energy is converted to useful turbine work. Losses come from the turbine itself (about 20%), incomplete expansion (20%), and the fact that this is a heat cycle that is not only Carnot limited but is limited by real cycle effects (again, about 20%). The combined losses come out to $0.8 \times 0.8 \times 0.8 = 0.5$ times the gas energy. Note that the net efficiencies in Fig. 1-6 fall short of what is achievable with very conventional thermal cycles.

We also explored the *Turbostar* concept with the bare target. In addition, we explored a scheme using the lithium sphere with mass addition (sodium or lithium) to lower

FIG. 1-6. Net conversion efficiencies for Turbostar case with lithium sphere sized for complete vaporization.

temperature for direct injection into a turbine. All three methods are compared with a simple thermal cycle in Fig. 1-7. As seen, none reach the original criterion of 70% conversion. And, because all of the direct recovery methods also require a bottoming cycle to achieve decent efficiencies, it is unlikely that they will offer any plant simplifications.

The thermal conversion seems to win out in the end. Not only is efficiency fairly high, but there is room for growth with advanced thermal cycles, and the nuclear island is kept relatively simple.

FIG. 1-7. Summary of power balance results for two Turbostar configurations, a direct turbine injection system, and a thermal system.

1.5. OTHER POSSIBILITIES

We briefly explored the horizontal jet concept shown in Fig. 1-8 as an alternative to Turbostar. This is a multipass system with annular jets having high enough velocity, about 80 m/sec, so that ballistic trajectories are nearly horizontal. For example, with 8 m length, deflection is 5 cm and 0.4 sec is needed between shots to reestablish the entire stream.

FIG. 1-8. Multiple liquid lithium reactor with bottom axis.
Top: Side view. Bottom: axial view.

The main advantage of horizontal placement is the ease in placing the final laser mirrors at the same elevation. The hot lithium can be directed to an advanced Brayton or Field cycle giving efficiencies near 50%.

1.6. CONCLUSIONS

Direct mechanical recovery of the non-neutron fusion energy requires the transfer of that energy to a working fluid that becomes pressurized to do work on the surroundings. Pressure is due to random thermal motion. Therefore, such "direct" recovery schemes are actually crude thermal cycles whose efficiencies are Carnot limited. It was found in this study that these attempts cannot compete with conventional thermal conversion systems. With efficiencies of 45% today and up to 55% projected in the future, direct mechanical conversion systems do not measure up. Their conversion efficiencies are much lower, and so a bottoming cycle is required. Although the combination of direct conversion plus bottoming cycle yields efficiencies near 50%, the added complexity does not appear to be justified.

It is recommended that we pursue advanced thermal cycles that yield both high efficiency and high reliability. With modern materials, the Rankine cycle can possibly be improved upon. Using ceramics, the Brayton cycle can produce efficiencies even over 55%. And the hybrid cycle, the Field cycle, offers a smooth transition from the Rankine to the Brayton and gives good efficiencies at moderate temperatures and pressures.

2. CASCADE ISSUES

Cascade is an innovative ICF reactor concept invented by LLNL^[2-1, 2] that employs a rotating bed of solid ceramic granules as first wall and blanket. The concept appears technically viable, is compact and very efficient, and has low cost and inherent safety. During FY84 and 85, GA developed reaction chamber and power conversion system designs. During FY86 we investigated several other issues. These are

1. combustion of the carbon surface layer,
2. consideration of alternate materials and flow rates, and
3. Cascade reactor plant costs.

Results of these investigations are described in this chapter.

2.1. CARBON SURFACE LAYER COMBUSTION

The Chernobyl fission reactor accident has raised sensitivities to the possibility of fires in reactors containing carbon. We examined the potential of this happening in the Cascade reactor, which contains carbon granules in the blanket.

2.1.1. Background

The Cascade ICF reactor concept^[2-1, 2] is a unique embodiment in which the lithium-bearing blanket consists of moving solid granules within a rotating reactor chamber (see Fig. 2-1). The features of the concept are high conversion efficiency, low activation, and no reactive lithium (the lithium is bound up in a ceramic lithium aluminate).

Originally, the Cascade blanket was to have a beryllium oxide (BeO) surface layer to absorb the surface heat flux from the pellet explosions. However, it was soon learned that

FIG. 2-1. The Cascade reactor concept.

when the beryllia dissociated, the noncondensable oxygen introduced excessive gas into the pellet chamber. To rectify this difficulty, the BeO front layer was replaced by a layer of carbon granules. While this solves the problem of gas evolution, it introduces a new problem of combustion in the event of accidental air ingress into the chamber. At issue is whether the carbon combustion would be sufficiently intense to volatilize the lithium aluminate in the breeding blanket so as to release activated aluminum to the environment.

2.1.2. Approach

The key concerns are the temperature of the carbon-air combustion products, whether they come near the melt or vaporization temperature of the lithium aluminate, and the magnitude of any overpressures resulting from the combustion. We therefore determined the adiabatic flame temperatures, energy releases, and overpressures for a number of fault scenarios.

2.1.3. Results

Activity release from melted or volatilized lithium aluminate is unlikely for the following reasons. If sufficient air is present, the carbon reacts to dioxide, releasing 33 MJ/kg carbon. If there is excess carbon, the monoxide reaction prevails and energy release is quite a bit less, 9.4 MJ/kg carbon.^[2-3] With the dioxide reaction, the adiabatic flame temperature, which is the highest temperature that can be reached, is, as calculated by the methods in Ref. 2-4, 2450 K. With monoxide, it is 1470 K. Lithium aluminate melts at around 2200 K,^[2-5] which is between these two. However, the BeO front layer, which is located between the LiAlO_2 and the carbon, never melts — its melting point is 2800 K. Therefore, the lithium aluminate will never be in direct contact with the flame and should never melt. Even if melting did occur, there would still be negligible transport of radioactive products. Vaporization is required, and temperatures never get that high. If the chamber stops rotating, then everything falls to the bottom. One would expect the carbon to be covered over by the other granule materials and so little air could contact it for combustion. Even then, unless the accident is truly catastrophic, it is unlikely that temperatures could get high enough to melt the lithium aluminate.

Provided the heat exchangers remain intact, they could remove the heat generated by the combustion. If the heat exchanger failed, the high pressure helium would of course purge the air out of the chamber and no combustion would occur. There are 53 tonnes of carbon granules in the whole system, including the heat exchangers.^[2-2] If all of this reacted to dioxide, which is highly unlikely, then some 1700 GJ of energy would be released. Considering that the heat exchangers are designed to remove about 1700 MW, then they could safely remove this heat in about 17 minutes. This is the worst case. If, as is more likely, all the carbon burns to monoxide, about 400 GJ are released. The heat removal time is then reduced to 4 minutes. More likely than the above, only the carbon in the reaction chamber will react as well as the small amount in flight because these particles are more likely to be exposed to air (the granules are tightly packed in the heat exchanger). Assuming the only air available is that which fills the vacuum chamber at one atmosphere.

the system is carbon rich and the monoxide reaction will prevail, releasing about 40 GJ. The peak overpressure would be 0.2 atmospheres, which is quite easy to design against since the chamber is already designed for one atmosphere overpressure. Of course, since the combustion required an air leak to occur, that overpressure would be vented through the same leak. If the heat exchanger were called on to remove the heat, it could do so in about 20 seconds. Because the combustion products would tend to block the flow of fresh air, combustion would probably be quite slow.

In summary, although combustion of the carbon granules is a concern that must be addressed, it is unlikely to generate temperatures or overpressures of sufficient magnitude to effect the release of activated aluminum from the lithium aluminate.

2.2. ALTERNATE GRANULE MATERIALS

Although the carbon granule combustion problem appears controllable, we nevertheless did briefly explore two other granule options: (1) replacing the carbon with beryllium, and (2) using instead a silicon carbide surface layer with a lithium oxide breeding layer (the BeO layer would be eliminated).

2.2.1. Beryllium Surface Layer

This might be a viable option despite the general discomfort with handling pure beryllium. Berylliosis, a lung disease resulting from inhalation of beryllium dust, has not appeared in chronic form since 1949 when controls were initiated.^[2-6] Hazard potential in a functioning reactor should be well under the hazard caused by the induced radioactivity.

There is the question of the amount of heating that beryllium can withstand before fracturing due to thermal stress. While this would require a complex stress analysis, a relative comparison with carbon is straightforward. The maximum thermal stress is given by

$$\sigma \leq \frac{E \alpha \Delta T}{2(1-\mu)}$$

where E is the modulus of elasticity, α is the thermal expansion coefficient, and μ is Poisson's ratio. The surface temperature rise from an energy flux ϵ per unit area over time t is given by^[2-7]

$$\Delta T = \frac{2\epsilon}{K} \sqrt{\frac{\kappa t}{\pi}} \quad , \quad \kappa = \frac{K}{\rho C_p}$$

where K is the thermal conductivity, ρ is the density, and C_p is the specific heat. Combining these two gives the ratio of allowable energy deposited on the surface of the granules of materials 1 and 2:

$$\frac{\epsilon_2}{\epsilon_1} = \frac{(1-\mu_2)}{(1-\mu_1)} \frac{E_1 \alpha_1}{E_2 \alpha_2} \sqrt{\frac{K_2}{K_1} \frac{\rho_2}{\rho_1} \frac{C_{p2}}{C_{p1}}}$$

Based on this thermal stress criterion, beryllium can take only about 0.04 times the energy dose as Poco graphite, an isotropic carbon with properties similar to granule-size CVD pyrocarbon. Actually, beryllium can probably take a little more because, having $Z = 4$, its near-surface deposition of X-rays will be less than carbon, which has $Z = 6$. Also, the failure mode should be more benign with Be: instead of pulverizing as the brittle graphite does, beryllium should yield and flow plastically. Therefore, even though the granules may deform, they may still be reusable. Nevertheless, a beryllium first layer would have to be considerably further from the target. Beryllium melts at 1557 K, which probably limits its maximum use temperature in our application to about 1300 K. This low temperature would make heat removal by radiation more difficult, although a metallic heat exchanger might be possible. Perhaps the beryllium could be at the low temperature side of the helium loop.

Any beryllium vapor should quickly recondense on cooler surfaces, mainly the remaining Be granules, after the surface heat has had time to soak through. The reaction to BeO gas is endothermic, that is, energy must be supplied and therefore a gas phase BeO will not form. A solid phase, however, probably will present no hazard.

2.2.2. Silicon Carbide/Lithium Oxide Blanket

One of the options considered in the Cascade Study^[2-2] was a blanket with a silicon carbide surface layer and a lithium oxide breeding blanket. This has the advantages of nil-induced activity, low vapor pressure dissociation products, and high thermal stress capability and high melting point of SiC. The more volatile dissociation product, silicon, limits postshot bulk surface temperature to about 2300 K based on 1.0 torr overpressure. In the Cascade study, power conversion efficiency was estimated to be about 5% less with SiC/Li₂O than the reference C/BeO/LiAlO₂ design although that now appears conservative and it should be possible to adopt this blanket with no power conversion loss.

A key question with this option is the temperature at the interface between the two materials. Because of the poor thermal contact between the granules, it may be possible to run the silicon carbide to a temperature somewhat higher than allowable in the lithium oxide. We assume this to be the case here. If this turns out to be wrong, it should still be possible to use these materials with an intermediate layer, either SiC (moving at a much slower velocity so that little mixing occurs) or BeO.

The heat exchanger heat line is shown in Fig. 2-2. With helium temperatures of 960 to 1300 K, efficiency should be 55% as before.^[2-2] The silicon carbide enters at 1900 K and leaves at 1300. The Li₂O enters at 1300 and leaves at 1200 K. The peak temperature of 1300 K is only slightly above the limit of 1200 K recommended^[2-1] based on LiOT diffusion into the reaction chamber.

The heat transfer coefficient, h , for radiation goes approximately like the cube of the mean temperature. The ratio of new to old heat exchanger areas is given by

$$\frac{A_{\text{new}}}{A_{\text{old}}} = \frac{f_{\text{new}}}{f_{\text{old}}} \frac{h_{\text{old}}}{h_{\text{new}}} \frac{\Delta T_{\text{old}}}{\Delta T_{\text{new}}}$$

where f is the fraction of the total 1700 MW of thermal power delivered to the heat exchangers and is 0.3 for the SiC and 0.28 for the carbon. The heat transfer coefficient for

FIG. 2-2. Heat line for SiC/Li₂O blanket option.

the carbon layer was 770 W/m² K; for the SiC it is 850. Log mean temperature difference also increases from 220 K for the carbon to 280 for SiC. With these changes, the new heat exchanger area for the silicon carbide granules is 0.76 times that of the old one for the carbon. The situation is different, however, for the lithium oxide. Compared to the lithium aluminate, the heat transfer coefficient goes from 490 to 260 W/m² K and the log mean temperature difference goes from 220 to 160 K. Further, the fraction of heat transferred increases from 0.59 to 0.70. The result is a heat exchanger for the Li₂O that is 3.1 times larger than for the lithium aluminate.

We can estimate the cost increase for the heat exchangers by ratioing the heat transfer areas, which is allowable because all three heat exchangers are of the same design. The heat exchanger areas for the carbon, BeO and lithium aluminate granules were^[2-2] 2600, 1600, and 9000 m, respectively. The ratio of new to old areas is then

$$\frac{A_{\text{SiC}} + A_{\text{Li}_2\text{O}}}{A_c + A_{\text{BeO}} + A_{\text{LiAlO}_2}} = \frac{1976 + 27900}{2600 + 1600 + 9000} = 2.26$$

To estimate the incremental increase in plant cost, we note from Ref. 2-2 that the related cost of the heat exchangers is \$40 million and the total capital cost is \$1034 million. The incremental cost increase for the heat exchangers is then

$$\frac{\Delta\$}{\$} = \frac{1.3 \times 40}{1034} = .05$$

This small increase could be completely offset by the reduced costs stemming from the lower induced activity in the blanket material if it becomes necessary to harden the reactor building due to the activated aluminum in the LiAlO_2 .

2.3. EFFECT OF REDUCED CARBON FLOW RATE

In Ref. 2-2, the volume flow rate of the carbon surface layer was $2.2 \text{ m}^3/\text{sec}$ and the temperature rise from inlet to outlet was 100 K. It has been suggested that this flow rate be reduced to $1.0 \text{ m}^3/\text{sec}$. In this section we examine the effect of this change on the heat exchangers.

With the lower mass flow, the carbon granule temperature rise increases from 100 to 220 K. If the outlet temperature is held to the original 1600 K, then the inlet temperature is reduced from 1500 K to 1380.

With radiative heat transfer, the heat transfer coefficient goes like T_{ave}^3 . Since T_{ave} goes from 1550 to 1490, the heat transfer coefficient for the carbon is reduced to 0.89 of its original value. Fig. 2-3 shows the heat line for the new carbon heat exchanger. The old log-mean temperature difference was 223 K. The wall temperature drop is reduced roughly in proportion to the granule side heat transfer coefficient because that side limits the heat transfer. The new log mean temperature difference is then

$$\Delta T_{\text{lm}} = \frac{(1600-1369) - (1380-1269)}{\ln \frac{1600-1369}{1380-1269}} = 164 \text{ K}$$

FIG. 2-3. Heat exchanger heat line for carbon granule flow.

The carbon granule heat transfer surface area ratio is then

$$\frac{A_{\text{new}}}{A_{\text{old}}} = \frac{h_{\text{old}} \Delta T_{\text{old}}}{h_{\text{new}} \Delta T_{\text{new}}} = \frac{1.0 \times 223}{.89 \times 164} = 1.53$$

The new heat exchanger must be 53% larger in surface area. The question now is how that area should be applied. From Ref. 2-2 the helium pumping power is 2.3% of the heat transferred, which is high enough. Fig. 2-4 shows the heat exchanger configuration to scale. The best way is to increase the height from 5.1 m to 7.8. This increases the helium cross sectional flow area by 1.53, which lowers the mass flow per unit area. The pumping power scales like $A/A_c = 1/1.53$ since the change in A , the heat transfer area, matches the change in A_c , the helium flow area. The pumping power is therefore reduced to 1.0% of the heat transferred. The heat transfer coefficient on the helium side is also reduced but, since the granule side limits the heat transfer, this has little effect. The cost increment, using the same scaling as earlier, is 10% for the total heat exchanger and 0.3% for the plant. The reduced helium pumping power frees up 10.6 MW, increasing the net

FIG. 2-4. Original carbon granule heat exchanger drawn to scale.

output from 815 to 826 MW, a 1.3% increase. Cost of electricity would therefore actually decrease about one percent despite the higher capital cost.

2.4. ELABORATION OF CASCADE COST ACCOUNTS

This section elaborates on the detailed cost elements presented in the Cascade final report.^[2-2] The Cascade design was costed in two different ways. The first was to cost it as if it were an advanced fission reactor. These costs are based on HTGR costs for the most part, because the Cascade system with helium cooling and a ceramic structure is much closer to an HTGR than it is to a PWR. The advanced HTGR costing assumes success in the studies presently underway to maximize the separation between non-nuclear and nuclear grade systems in order to reduce costs. Both HTGR and light water reactor groups are now pursuing these "separation criteria" in developing advanced designs for more cost effective fission reactors. We believe that the competition for fusion in the future will not be present day fission reactors but advanced future fission reactors. We are therefore using these advanced fission reactors as the beginning of our cost basis. The first method to cost the Cascade reactor then is this advanced fission reactor basis where some

components need a nuclear stamp and some use conventional construction. The sum of the two gives the total cost of a nuclear-type system.

The second way that the Cascade ICF reactor was costed was to make the assumption that no nuclear stamp qualification of any kind would be needed. The costs instead were derived primarily from coal-fired power plants. Note that there is a significant cost differential between the fission rated costs and the non-nuclear costs. The total direct capital cost difference is approximately 15%; the total direct plus indirect capital cost difference is about 26%. Thus there is a significant economic incentive to try to avoid N-stamp requirements for fusion reactors. The basis for costing Cascade as an all non-nuclear system is described in detail in the final report.^[2-2] Based upon the higher level regulatory criteria, primarily 10CFR100, no nuclear stamp qualification should be required for Cascade. The maximum vulnerable inventory of tritium in Cascade can be kept below 200 g. This limits the site boundary dose during a total release accident to less than 20 rems.^[2-2] The stored chemical and nuclear energy in the Cascade plant is so small that we believe there is no way a significant fraction of the very small amount of radioactivity present in Cascade could be transported to the site boundary. As a result, the very low quantity of radioactivity in the plant will not contribute to the site boundary dose rate during any credible accident. On the basis of these analyses, we believe that, under any conceivable accident, total failure of all reactor systems will not result in a site boundary dose rate in excess of 20 rems. This means that, under 10CFR100 guidelines, N-stamp qualifications of any kind will not be required.

The Cascade costing was reviewed independently by MacDonnell-Douglas Astronautics Co. (MDAC) as part of a larger review project.^[2-8] MDAC arrived at a number of cost differences mainly because they did not account for the dual nature of the cost issue described above. Table 2-1 below addresses the specifics of these cost differences. The Cascade (GA) costs are for 815 MW(e) net output. The MDAC costs were for 1000 MW(e). For simplicity, we have scaled them back to 815 MW(e) according to $P^{0.8}$.

Table 2-1
Detailed Resolution of Cost Discrepancies
between Cascade (GA) and MDAC

Account No.	GA* \$M	MDAC** \$M	Comments
211 - Site Improvements and Facilities	7.0	14.4	We have scaled our costs from a Bechtel study of the 1050 MW(t) HTGR plant, which takes full credit for "separation criteria." MDAC costs appear to come from EEDB "best estimate" current fission reactor costs, and do not take any credit for improved separation criteria.
212 - Reactor building	26.4	42.5	Our unit cost basis is given in Ref. [2-2]. MDAC cost uses the same unit cost, but assumes a larger building is needed for disassembly and laydown of the components. The reaction chamber lifetime in Cascade is the entire plant lifetime of 30 full-power years. Thus, there is no scheduled disassembly of the Cascade chamber and does not, therefore, need disassembly and laydown space. In the advent of an unanticipated failure of the system, we would propose to take the roof off the building because it is a low activation system, and to perform maintenance with special rigging.
261 - Heat rejection structures	2.8	2.8	Both the HTGR and EEDB use a wet cooling tower. But our estimate of 0.8 was unusually low. We recommend using the MDAC \$3.3M estimate scaled to 815 MW.
222 - Blanket	45.4	45.8 8.5 helium 0.6 misc.	We have included the initial and makeup helium cost in the \$50M/yr operating and maintenance costs. This is standard procedure for the HTGR. Thus, we do not believe the MDAC addition here is justified unless it is subtracted from the O&M cost. We know of no reason why there should be an additional \$0.7M miscellaneous cost. Thus, account 222 should simply be our blanket costs scaled to the larger power, of the MDAC study, or \$54M.

Table 2-1
Detailed Resolution of Cost Discrepancies
between Cascade (GA) and MDAC
 continued

Account No.	GA* \$M	MDAC** \$M	Comments
228.1 - Atmospheric detritiation systems	4.6	41.6	Our basis is the fairly detailed design and description given in the MARS final report. The MARS final cost was \$21.3M for a detritiation system capable of recovering 30 Ci/d with a flow rate of 417 m ³ /min. The Cascade system is \$4.6M based upon a leakage rate of 0.3 Ci/d and a 4 m ³ /min cleanup system.
25 - Reactor maintenance	16.3	42.8 plant 12.1 reactor	Most of the GA cost is for the air and water systems. This is based upon the HTGR design. We have no special maintenance equipment provided. The reactor chamber lifetime is the full reactor plant lifetime. Contract maintenance is allowed for all routine repairs and replacement in the steam generator region, and the dose rate within the reactor chamber itself is low enough (2 rem/hr) that local shielding and rigging would suffice for handling in the case of an unanticipated failure. Thus, we believe that our estimate of \$16.3M is more realistic.
229 - Instrumentation	8.1	21.2	The GA instrumentation and control cost was taken directly from our 1170 MW(t) HTGR design without any scaling. This design was done in considerable detail, including the instrumentation and control system, and we believe that it is perfectly applicable to Cascade. There may be additional instrumentation and control associated with the laser systems. We assume that these are included within the laser plant equipment. Thus, we recommend using the \$8.1M number.

* 815 ME(e) for sale.

* Scaled to 815 MW(e) from 1000 by P^{0.8}

3. ICF INNOVATIVE CONCEPTS PROGRAM

The principle charter for GA's effort in FY86 was to explore innovative ICF reactor ideas that have the potential of raising efficiency, lowering cost, and simplifying the reactor plant.

3.1. OBJECTIVE AND SCOPE

The purpose of this effort was to explore innovative ways of directly recovering the non-neutron energy from a pellet explosion as efficiently as possible. This energy, which typically comprises 35-40% of the total fusion energy from the D-T target, is in the form of particle kinetic energy and electromagnetic radiation. It is largely a surface heat load, although there are some X-rays that penetrate slightly.

The suggested criteria for selecting concepts were to obtain at least a 70 percent conversion efficiency without noticeable cost or reliability penalties, or to achieve a significant simplification of the entire power plant at normal efficiencies. We considered the following concepts conceived by GA and discussed in detail in this section:

1. Ablation Turbine,
2. Liquid Piston,
3. Wave Generator, and
4. Resonant Pump.

We also explored the Turbostar concept conceived at LLNL.^[3-1] This is discussed at length in Section 5.

3.2. ABLATION TURBINE

When target plasma and X-ray energy strike a reaction chamber wall, material is ablated away, generating an impulsive load on that wall. If that impulsive loading could be exploited, it would be possible to directly recover that otherwise thermalized energy.

3.2.1. General Principles

The basic idea of this concept is to vaporize a small fraction of material from the blades on the spinning turbine wheel so that the impulse generated by the material blown off drives the wheel. The surface vaporized would be replaceable such as, for example, a liquid metal film. Fig. 3-1 shows the original concept. Fig. 3-2 shows the velocity diagram for the blowoff. The blowoff motion is perpendicular to the surface of the blade regardless of the incident angle of the target energy. This assumes diffuse rather than specular reflection of the energy, which is appropriate when the energy is first deposited into the surface layer and then the vaporized material blows off. A thin surface layer is typically blown off. The blowoff velocity is proportional to the blowoff impulse:

$$V \sim I \sim \sqrt{\epsilon_{\text{blowoff}}} \sim \sqrt{\epsilon_{\text{dep}}} ,$$

The blowoff energy is proportional to the energy deposited and

$$\epsilon_{\text{dep}} = \frac{E_o}{\ell \sin \theta}$$

E_o is the incident energy from the target per unit depth and ℓ and θ are shown in Fig. 3-2. Since $u = V \cos \theta$, the tangential component of kinetic energy, which does the useful pushing on the blade, is

$$KE_{\text{tan}} \sim u^2 \sim \sin \theta \cos^2 \theta$$

The angle where this tangential kinetic energy is maximum is where

FIG. 3-1. Original concept for the ablation turbine.

$$\frac{d}{d\theta}(u^2) = 0 = -2 \cos \theta \sin^2 \theta + \cos^3 \theta$$

or

$$\tan^2 \theta = \frac{1}{\sqrt{2}}, \quad \theta = 35.3^\circ$$

The maximum energy efficiency is then

$$\eta_m = \frac{u_m}{V} = (\cos 35.3^\circ)^2 = 0.67$$

This approaches our limit of 70%, but without including the losses due to blowoff coupling, matching blade speed with blowoff speed, and interference between blowoff and

FIG. 3-2. Blowoff velocity diagram.

blades. This maximum efficiency is possible when the residual velocity of the blowoff gas is reduced to a minimum, which occurs when the tip speed of the blade is equal and opposite the tangential component of the blowoff velocity. This constraint severely limits the magnitude of the blowoff velocity to several hundred meters per second, too low for significant impulse levels to occur unless a large mass is blown off, which is unlikely.

There are possible gains from multiple reflections. This will be covered later. First, one must understand the basics of blowoff impulse. Consider a blade with unit area and total thickness $t_1 + t_2$ where t_1 is the thickness of the material blown off and t_2 is the thickness of the remaining blade. From conservation,

$$m_1 u_1 = m_2 u_2$$

or

$$\rho_1 t_1 u_1 = \rho_2 t_2 u_2$$

The kinetic energy is

$$KE = \frac{m u^2}{2} = \frac{\rho t u^2}{2}$$

and therefore if, for simplicity, we assume $\rho_1 = \rho_2$,

$$\frac{u_2}{u_1} = \frac{t_1}{t_2}$$

and

$$\frac{KE_2}{KE_1} \approx \frac{t_1}{t_2}$$

The efficiency is given by

$$\eta = \frac{KE_2}{KE_1 + KE_2} = \frac{1}{t_2/t_1 + 1} \quad (1)$$

Eq. (1) will be plotted later with other efficiency numbers. This shows that, in order for the blade to capture most of the available kinetic energy, more material must be blown off than left on the blade, which is unlikely. Therefore, unless the kinetic energy of the blowoff is somehow recovered to drive the blades, kinetic energy coupling from blowoff impulse will be very inefficient. Further losses occur from the blade angle dependence discussed above but not included here.

The above of course assumes that any impulse delivered to the blade from the target blast debris is negligible. That this is so is seen by noting that the ratio of impulse to kinetic energy is $2/V$, where V here is the target debris velocity. Considering that the debris is at a stagnation temperature of perhaps tens of eV, then the resulting particle velocity is exceedingly high, and so little impulse will be delivered for a given energy. The impulse is generated when more mass at lower velocity is introduced through the blowoff process.

3.2.2. Multiaxis Ablation Turbine

The multiaxis ablation turbine was conceived to recover the kinetic energy from the high speed blowoff gas. It is shown conceptually in Fig. 3-3. It consists of an enclosed box whose sides rotate around axes at the corners. The length of the rotating members is $1/2$ times the spacing between axes so that they clear each other as they pass the center. In the microseconds after a pellet explosion, the intention is for the blow off gas to interact with the walls thereby delivering additional impulse each time. We examine two one-dimensional cases: (1) the blowoff sticks to the opposite blade and (2) the blowoff bounces elastically several times. In each gas we ignore expansion of the blowoff gas and treat it as a slug of material that bounces without being otherwise altered. This assumption is of course quite optimistic as gas expansion would lower the available directed kinetic energy that could be imparted to the blades.

Case 1: Blowoff Sticks - This case is shown schematically in Fig. 3-4. Simplifying to a one-dimensional model, the blowoff from the opposite blade strikes the blade and sticks. Momentum is conserved but kinetic energy is not. If the vapor recondenses quickly, as appears likely (Ref. 3-2), this is the likely process. With a simple model using constant blowoff density, from momentum conservation

$$t_1 u_1 + t_2 u_2 = (t_1 + t_2) u_3$$

or, since $t_1 u_1 = t_2 u_2$,

$$u_3 = \frac{2t_1}{t_1 + t_2} u_1$$

The resulting kinetic energy KE_3 is

FIG. 3-3. Multiaxis ablation turbine schematic.

$$\begin{aligned}
 KE_3 &= \frac{1}{2} m_3 u_3^2 = \frac{1}{2} (t_1 + t_2) u_3 \\
 &= \frac{1}{2} (t_1 + t_2) \frac{4t_2 u_1}{(t_1 + t_2)} \\
 &= \frac{2 t_1}{t_1 + t_2} u_1 .
 \end{aligned}$$

The initial kinetic energy was $KE_1 + KE_2$ which, after allowing for the fact that $t_1 u_1 = t_2 u_2$, is given by

$$KE_{init} = \frac{1}{2} t_1 u_1 \left(1 + \frac{t_1}{t_2} \right) .$$

FIG. 3-4. Multi-axis turbine. Sticking blowoff model.

The energy efficiency is then given by

$$= \frac{KE_3}{KE_{init}} = \frac{4}{(1 + t_2/t_1)(1 + t_1/t_2)}$$

This will be plotted later and compared with results from elastic bounces.

Case 2: Blowoff Bounces – This case is shown for four bounces in Fig. 3-5. It is contingent upon obtaining noncondensable blowoff gases that do not stick to the walls. It also requires that the bounces occur in such a way that the ablated particles do not interact with each other. Mean free paths must therefore be large, which in turn dictates that the mass of blowoff be small. Bouncing might occur for example with water, which would dissociate into hydrogen and oxygen and not recombine until considerable cooling had occurred. We would need to find a similar substance which has a higher melting point and a vapor pressure low enough for reaction chamber usage.

FIG. 3-5. Ablation turbine with blowoff bouncing off opposite blades. Shown for four bounces.

The analysis of the multiple bounce case is straightforward. The one-dimensional simplification with constant blowoff density is used again. Since it is the product ρt that matters, the momentum and energy analysis is unaffected. After the pellet explosion, the blade and blowoff velocities are ratioed by the fact that the net momentum is zero:

$$t_1 u_1 + t_2 u_2 = 0$$

After the first elastic bounce (see Fig. 3-4), since both momentum and energy are conserved:

$$t_1 u_1 + t_2 u_3 = t_1 u_4 + t_2 u_5 \quad \text{and} \quad (2)$$

$$t_1 u_2 + t_2 u_2 = t_1 u_4 + t_2 u_5 \quad (3)$$

Eqs. (2) and (3) can be recombined as follows

$$t_1 (u_1 - u_4) = t_2 (u_5 - u_3) \quad (4)$$

$$t_1 (u_1 - u_4) (u_1 + u_4) = t_2 (u_5 - u_3) (u_5 + u_3) \quad (5)$$

and, after dividing Eq. (4) by Eq. (3), one obtains

$$u_1 + u_4 = u_5 + u_3 \quad (6)$$

Eq. (6) can be solved for u_5 and substituted into Eq. (2), which can then be solved for u_4 knowing that $u_3 = u_2$, and that u_2 is known. This procedure can be continued for as many bounces as desired. We define the efficiency as the kinetic energy of the blade divided by that energy plus the kinetic energy of the blowoff. Results for one through four

bounces are shown in Fig. 3-6. Also shown is the case for sticking blowoff presented earlier. The first point worth noting is that efficiencies approaching 100% are possible with just a few elastic bounces. This is because the blowoff is brought virtually to rest. Unfortunately, the second point is that this high efficiency occurs when the blowoff thickness is rather high, several percent of the blade thickness. This is because then the disparity between blade and blow off velocities is less and only a few bounces are needed to extract virtually all of the blowoff energy. The problem is that blowoff thicknesses have been calculated to be very small, one micron or less (Ref. 3-3). Assuming a reasonable blade thickness of, say, one centimeter, then t_1/t_2 is more likely to be less than 10^{-4} , where efficiency after four bounces is only a few percent. If one could project several thousand bounces, then perhaps there would be hope for reasonable efficiency. But this is unlikely due to the inherent randomization of the reflecting process which was neglected for simplicity in this analysis. In reality, the blowoff quickly expands to fill the chamber and leak out the ends.

3.2.3. Conclusion

It is because of this poor expected efficiency that we have discarded the ablation turbine for now. However, some of the thinking that has evolved from the analysis, in particular the search for noncondensable blowoff products, may eventually aid in the development of a concept that is efficient, although none at the moment have appeared on the horizon.

3.3. LIQUID PISTON

While the ablation turbine was gas-dynamic in nature, the liquid piston is hydraulic. It is a cyclic device where noncondensable gases blown off a wetted wall drive a liquid column through a hydraulic turbine. The liquid contains a lithium-bearing substance which supplies the necessary tritium. After passing through the hydraulic turbine, the liquid is sent to a heat exchanger to extract the remaining energy and then to a tritium recovery system. The sequence of operations is shown in Fig. 3-7. It is a multicylinder device with spinning mirrors flashing the laser light to successive cylinders and rotating

FIG. 3-6. Blade efficiency for ablation turbine for one to four elastic bounces and for inelastic (sticking) case. Also shown is the no bounce case where the blowoff expands to infinity. Unfortunately, the likely state is well to the left of the graph.

valves providing timed light apertures and alternating pressure seals. All cylinders are joined to a common manifold and a smoothed liquid flow passes through a single turbine and heat exchanger.

The sequence proceeds as follows: The liquid chamber is first filled to the top (Fig. 3-7a). The vacuum valve at the bottom of the chamber is then drawn down, which creates a vacuum at the top of the chamber equal to the vapor pressure of the liquid (Fig. 3-7b). Both the feed valve at the top and the rotating valves are closed at this point.

Inertia retards backflow through the quickly opened vacuum valve. The rotating valves are then quickly opened, and a pellet is injected and imploded by the laser. The rotating valves then close and the overpressure generated by vaporization of the wetted wall closes the top feed valve and drives the liquid level down such that the gas expands over a considerable expansion ratio (Figs. 3-7c and d). The work produced by the expansion is

$$W = \frac{P_1 V_1}{1 - k} \{ (V_1/V_2)^{1-k} - 1 \}$$

Fig. 3-8 shows the ratio of work out to that for an infinite expansion as a function of volume expansion ratio for two values of k : 1.4 (diatomic gas) and 1.67 (monatomic). Clearly, the higher the expansion ratio the more work produced. However, system bulk increases as well because system volume is determined by the the gas volume at the end of expansion which, for a given work output, is proportional to the expansion ratio. We have chosen an expansion ratio of 8.0 as a suitable compromise because it is near the bend in the curve.

How closely the actual expansion follows this ideal gas depends on the initial degree of superheat and on the time available for heat transfer between the liquid film and the gas. The longer the time, the more mass will be vaporized but the closer the superheated gas will move toward saturation. If the gas is near saturation, some condensing will occur during expansion. Although the expansion remains essentially isentropic after temperatures

FIG. 3-7. Liquid piston system operational sequences.

drop to the point where little further heat transfer occurs, the available work produced diminishes because of the reduced gas phase available.

FIG. 3-8. Ratio of work out for a given expansion ratio to that for an infinite expansion ratio for diatomic ($k=1.4$) and monatomic ($k=1.67$) gases.

As the gas expands, liquid is pushed into the manifold that serves all the cylinders. This liquid has also been heated by neutrons, and that thermal energy is extracted after the PV work is extracted by the hydraulic turbine. The residual gas in the chamber is cooled during the expansion and then condensed by the subcooled liquid entering from the top fill valve.

This system would make efficient use of the non-neutron energy because the expansion would be virtually isentropic. However, it is not very compact. For example, with a typical pellet explosion producing 100 MJ of non-neutron energy, an initial volume of six cubic meters is needed to hold the gas pressure to 100 atmospheres. For an eight-to-one expansion, the cylinder must displace 50 cm³. Assuming flow velocities are no more than 20 m/sec to keep friction low, then cycle times would be 1-2 seconds. For a desired 5 Hz

rep rate, 5-10 cylinders would therefore be needed. Of course, these multiple cylinders would smooth the power flow to the turbine.

A better approach seems to be what is usually done for high power levels: replace the piston/cylinder with a turbine and PV work with high velocity kinetic energy. This is the Turbostar approach and its variations that will be addressed later.

3.4. WAVE GENERATOR

The wave generator is a concept in which the blast energy creates a "splash" in a rotating liquid metal column (see Fig. 3-9) which generates surface waves that propagate outwards. Their energy is collected at the end by a wave energy extractor. Nuclear heating is absorbed in the liquid metal as is usual. This concept requires good transference of the blowoff energy to wave energy. However, the efficiency problems associated with the ablation turbine occur here as well. The blowoff will recondense and the kinetic energy will turn to heat. Worse, the potential energy density in waves of practical heights is at least two orders of magnitude below what is required even at the high g-loads associated with the rotation. Therefore, this concept was discarded.

3.5. RESONANT PUMP

The resonant pump is an idea whose initial motivation was to provide a way of building up a substantial head by accumulating the energy from a number of small impulses from pellet explosions. The concept is shown in Fig. 3-10. A U-shaped column of liquid metal is set to oscillating by the timed impulses from pellet explosions. Each burst provides enough energy to overcome friction and also raise the amplitude of the oscillations until a level is reached when the column spills over into a "pond" that provides a constant head to the hydraulic turbine. The liquid metal recirculates automatically because the head at the pond exceeds the mean head in the resonating column.

The concept was mistakenly adapted from a unique pump developed years ago by L. Crendon *et al.*, (Ref. 3-4) to dry out flooded construction sites. It is shown schematically

FIG. 3-9. Wave generator concept.

in Fig. 3-11. The system consists of a piston pump with a one-way valve, three plena to smooth pressure spikes, and a small diameter discharge tube. In operation, a downstroke of the piston causes the one-way valve to open and fill the cylinder with fluid. An upstroke closes the valve and pumps the fluid into the small discharge tube where it is accelerated to high velocity. At the end of the stroke, the inertia resulting from that kinetic energy pulls more fluid through the one-way valve thereby creating an apparent volumetric efficiency of much greater than 100%. The advantages are a smaller and lighter pump for a given volume flow and better coupling to existing motors such that the need for a gear reduction is eliminated. But note that it is not a resonating system. In fact, the three plena were installed to damp out resonances. In many ways, the Turbostar concept is similar in which liquid metal is accelerated through nozzles. Perhaps, if the high velocity stream is made long enough in Turbostar, we will be able to exploit the inertial effect. As far as the resonant pump is concerned, the inertia pump has little bearing.

FIG. 3-10. Resonant pump concept.

The realities of the resonant pump are that each pellet explosion is quite massive and requires no accumulation of head. If the 100 MJ of pellet blast energy created a volume of gas 2 m diameter, the pressure of that gas would be over 100 atmospheres, hardly in need of multiplication. Also, the internal energy of a resonating system is not available for external use. If drawn away, the resonance stops. The internal energy of the system has considerable friction associated with it, which would consume much of the pellet output. Finally, the original concept was intended to capture the impulse from uncontained pellet

FIG. 3-11. Inertial boost pump that served as basis for the resonant pump concept.

explosions in order to keep reaction chamber pressure down, although as the concept proceeded that notion became blurred. But we have already seen that the energy coupling from uncontained blowoff is extremely poor unless the blowoff is very thick, which hydro calculations show not to be the case.

Because of all of these flaws, the concept was discarded. Some of the ideas gleaned, however, particularly from the inertia pump, may eventually be applicable to Turbostar or its possible descendants.

3.6. SUMMARY

We explored four innovative concepts for direct recovery of the non-neutron energy from a fusion target, which typically comprises 35-40% of the total:

1. Ablation turbine,
2. Liquid piston,
3. Wave generator, and
4. Resonant pump.

After sufficient analysis for reasonable understanding, none show any advantage over a simple thermal conversion system. While in principle one could conceive of highly efficient conversion because of the high specific energies, in practice this is very difficult to obtain.

The positive benefit of this exercise has been increased sophistication in the processing of creative ideas. This is a research program and therefore the more ideas generated the better. But most ideas are simply no good. Yet without the struggle to generate these bad ideas, the good ones will never emerge. What is necessary is to have a lot of ideas, and then have a mechanism whereby the bad ones, which are the majority, can be spotted and quickly discarded so that more time can be spent on the promising ones. The sophistication lies in the development of techniques to evaluate each idea until a fatal flaw is uncovered. This project has moved us a considerable distance in that direction.

4. TURBOSTAR

The Turbostar concept was originated by LLNL^[4-1] in an attempt to recover the non-neutron energy released from a fusion reaction directly and efficiently without recourse to a thermal conversion system. In D-T fusion, 80% of the energy release is in the form of energetic neutrons while 20% is in energetic alpha particles. In inertial confinement D-T fusion, a portion of the neutron energy is absorbed in the highly compressed fusion target. This lowers the fraction of energy carried away in neutrons to 60-65% depending on target details and yield^[4-1] and increases the non-neutron fraction to 35-40%. The latter is in the form of photon radiation and energetic particles which heat the surface of the reactor material facing the target. It is this non-neutron energy that the Turbostar concept is attempting to recover directly.

Conventional thermal systems are actually quite efficient, and so the criteria used to evaluate direct recovery must be rather stringent. Steam power plants now in operation achieve 45.5% efficiency,^[4-2] excluding losses out the exhaust stack, with supercritical main steam and one reheat (both at 540°C) and cold ocean water cooling. Advanced Brayton and Field cycles should be capable of 50-55% net efficiency^[4-3] using nickel-based alloys and ceramics. These high efficiencies with thermal systems underscore our evaluation criteria for the innovative concepts discussed in section 3 of 70% conversion efficiency without noticeable cost increase, or significant simplification and cost savings over a thermal system at nominal efficiency. The same criteria was also applied to Turbostar.

4.1. DESCRIPTION OF TURBOSTAR CONCEPT

The original Turbostar concept proposed by LLNL is shown in Fig. 4-1. It consists of an annular space through which flows a lithium-bearing liquid metal, channels to direct

this flow to turbines, and closure plates to maintain gas pressure. In operation, the liquid metal flows radially inward in the top annular conduit, then downward in such a way that a cylindrical hole is maintained into which is injected a fusion target. This target is illuminated through holes in the top and bottom closure plates, which then rotate shut to contain the gas pressure generated by vaporized liquid metal. The impulse thus generated drives an annular slug of that liquid metal into the several turbine inlet channels. After having their kinetic energy extracted by the turbines, the hot, but slowed, liquid metal is directed to the heat exchangers of a thermal conversion system. The liquid metal that is not so directed falls to the bottom and is recirculated to the top. Because it has had little thermal energy input, it need not flow to the heat exchangers.

Another embodiment of the same idea is shown in Fig. 4-2. Detail changes include closure valves with axes of rotation perpendicular to the major centerline. It is felt that this type of valve offers more positive sealing, stiffer structure, and simpler bearing design. Other changes include protruding lips in the upper and lower flow channels with void spaces above the fluid surfaces. This feature retards the propagation of the pressure in the central channel by requiring gross fluid motion for pressure buildup rather than simple shock propagation. If these pressures were to propagate throughout the system, massive restraining structures would be required. Another, and minor, change is the depiction of the recirculating pumps on a common shaft with the turbines. Such a coupling, if feasible, eliminates expensive pump drive motors.

4.2. BASIC POWER FLOWS

A schematic of the general power flow for Turbostar is given in Fig. 4-3. The four-to-one mix of neutron and alpha power is altered because of the absorption of neutrons in the highly compressed target. The resulting power breakdown is more like 35-40% non-neutron in the form of X-rays and pellet debris.^[4-1] As discussed later, this fraction can be increased by placing a close-in solid lithium sphere around the target with apertures to allow beam passage. If f_{n1} is the fraction of neutron power absorbed by the target debris

FIG. 4-1. Original Turbostar concept proposed by LLNL.^[4-1]

FIG. 4-2. Alternate Turbostar embodiment.

and f_{n2} is the fraction absorbed by the lithium sphere, then, referring to Fig. 4-3,

$$P_{x-D} = P_a + f_{n1} P_n$$

$$P'_n = (1 - f_{n1}) P_n$$

$$P'_{x-D} = P_{x-D} + f_{n2} P'_n - P_{x \text{ loss}}$$

$$P_n'' = P_n' - f_{n2} P_n' - P_{n \text{ loss}}$$

$P_{x \text{ loss}}$ and $P_{n \text{ loss}}$ are losses out the ends of the reactor chamber and are expected to be a few percent at most. As discussed below, the lithium sphere is useful in converting a large fraction of neutron energy to X-ray and debris energy for use in a direct mechanical convertor. The powers P_{x-D}' and P_n'' are intercepted by the lithium fall. All of the X-ray and debris energy and a small portion of the neutron energy accelerates the fall into a turbine (see Figs. 4-1 and 4-2). A portion of the turbine energy is recycled to pumps to drive the fall. The rest can go to electricity. The neutron energy is multiplied slightly during absorption in the fall. This thermal energy plus any losses through the turbine are converted to electricity in a bottoming cycle. Referring again to Fig. 4-3, with P_B defined as the fall thermal power and P_{dir} as the fall kinetic energy, the various powers are given by,

$$P_{dir} = P_{x-D}'$$

$$P_{e1} = \eta_T P_{dir} - P_p$$

$$P_B = M P_n''$$

$$P_{th} = P_B + (1 - \eta_T) P_{dir}$$

$$P_{e2} = \eta_{pc} P_{th}$$

The net efficiency is given by

$$\eta_{net} = (P_{e1} + P_{e2}) / P_{fusion}$$

FIG. 4-3. Turbostar power flow schematic.

Clearly, the lithium sphere will have a considerable influence on power balance. This is analyzed below and is followed by the power balances of various configurations.

4.3. ANALYSIS OF CLOSE-IN LITHIUM SPHERE

In order to maximize direct mechanical conversion of the fusion power, it is desirable to maximize the gas generated by vaporization of the material in which the fusion energy is deposited. Because of the radial falloff of energy intensity, one must place material as close to the target as possible to maximize the gas temperature achieved. We consider a solid lithium (or lithium-lead) sphere with a through hole drilled along a diameter and the fusion target placed in the center. The target is illuminated via these holes.

Because the target is at about 20 K, the material surrounding it must be at a similar temperature or the target will boil. If the entire sphere is chilled, too much energy goes into refrigeration, as shown below. To chill one kg of lithium from 293 K to 20 K takes

$$E_{293} = C_p T = 3500 \frac{J}{kgK} (293 K) \\ \approx 10^6 J/kg$$

(Because the heat capacity in metals is very low at 20 K, the residual energy at that temperature is nil). Real cryogenic refrigeration systems have coefficients of performance (COP) of about 1/5 the theoretical Carnot value^[4-4] or

$$COP \approx \frac{1}{5} \left[\frac{20}{293 - 20} \right] = 1.5 \cdot 10^{-2}$$

and so the total energy required to chill 1.0 kg is

$$\epsilon_{in} = \frac{E_{293}}{COP} = 70 MJ/kg$$

We show later that the radius to vaporization is 10–15 cm for targets in the 2000 MJ range. A 10 cm radius lithium sphere weighs about 2 kg. So it would require over 150 MJ to chill it down, or about 8% of the total fusion energy. This is excessive, particularly when it can be reduced so easily.

If instead, a small cylindrical insert containing the target is chilled and this is inserted into a room-temperature lithium sphere (see Fig. 4-4), the mass that must be chilled is reduced to about 0.35 kg, assuming the tube to be 4 cm radius, 20 cm long, and having 30% void. The cooldown energy is reduced to

$$E_{in} = m \epsilon_{in} = 25 MJ$$

which, as a fraction of the 2000 MJ fusion yield, is

FIG. 4-4. Close-in room temperature lithium sphere with cylindrical insert and target chilled to 20 K.

$$\frac{E_{in}}{E_{fus}} = \frac{25}{2000} = .013$$

Note that, upon assembly, the chilled insert will expand and lock into the sphere. This would be done just prior to injection in the reactor chamber.

We now explore the deposition of neutron energy into the lithium sphere. The neutron energy deposition per unit volume can be approximated by

$$\epsilon = \epsilon_o \left(\frac{r_o}{r} \right)^2 e^{-r/\lambda} , \quad \frac{J}{m^3} \quad (1)$$

where the inverse square attenuation is due to the spherical geometry and the exponential e-fold λ depends on the material and the neutron spectrum. As one moves further into the material, the neutron spectrum becomes increasingly thermal and the attenuation is

greater so that, in reality, deposition profile is more complex than a simple exponential. Over the distances of interest here, that effect is minor, and so we adopt the simplification of a single e-fold factor.

The initial value E_o is determined by noting that the energy flux per unit area crossing the surface at r_o is

$$\Gamma_o(r_o) = \frac{E_n}{4\pi r_o^2} \quad (2)$$

where E_n is the fusion neutron energy. This flux attenuates in the same way as the volumetric heating:

$$\Gamma = \Gamma_o \left(\frac{r_o}{r} \right)^2 e^{-r/\lambda_1} \quad , \quad \frac{J}{m^2}$$

Because of the shifting neutron spectrum, λ will differ from λ_1 at some depth into the material. At the initial surface, however, no such shifting has taken place and so $\lambda = \lambda_1$. The initial value of volumetric heating E_o is found from

$$\epsilon_o \equiv \epsilon(r_o) = -\frac{dT}{dr} = \frac{\Gamma_o}{\lambda} = \frac{E_n}{4\pi r_o^2 \lambda}$$

Figure 4-5 shows deposition profiles for two materials, pure lithium and $\text{Li}_{17}\text{Pb}_{83}$, a eutectic. The lead increases the attenuation rate slightly and provides for slightly greater peak heating near the center. Because the lithium lead suffers from activation of the lead, we will limit this discussion to the low activity pure lithium.

Figure 4-6 shows the energy line for lithium. Of special interest is that the energy input required to bring it to saturated vapor is about 27 MJ/kg. Figure 4-7 shows saturation intercepts for lithium spheres for two neutron yields, 132 and 1320 MJ (200 and 2000 MJ total fusion energy). The lithium is turned to superheated vapor inside a radius of 5 cm for the lower yield and 12.5 cm for the higher. These would be the chosen dimensions for the lithium sphere that serves as a gas generator. If made larger, the nonvaporized

FIG. 4-5. Spherical deposition profiles for lithium and lithium-lead normalized to incident flux at r_0 .

lithium would be accelerated by the gas to high impact velocities against the lithium fall. It is doubtful that this would be of any benefit compared to driving the fall by the gas ball. The preferable gas lithium sphere radius is then the radius out to saturated vapor. Figure 4-8 shows this radius as a function of total fusion yield.

It is assumed that pressure and temperature will equilibrate throughout the gas ball. The mechanism would probably be by a series of pressure oscillations that redistribute the high central pressure to the edges of the sphere, adiabatically lowering the central

FIG. 4-6. Energy line for lithium at solid density. Also shown is a graphical representation of the equation of state for lithium at high pressures.^[4-5]

temperature and raising that at the edge. The average gas ball energy afterwards is given by

$$\begin{aligned} \langle \epsilon \rangle &= \frac{1}{V} \int_0^{r_v} \epsilon dV \\ &= \frac{3E_n}{4\pi r_v^3} \left(1 - e^{-r_v/\lambda} \right) , \quad \frac{J}{m^3} \end{aligned}$$

FIG. 4-7. Nuclear heating profiles in lithium sphere for two fusion energy levels, 200 and 2000 MJ.

Figure 4-9 shows this average gas energy normalized to the saturated vapor energy (27 MJ/kg). Also shown is average temperature in eV and pressure at solid density. The temperature is based on an assumed constant heat capacity of 3 KJ/kg for the lithium vapor. The pressure is based on the equation of state curves shown in Fig. 4-6. Clearly, in all cases the gas energy is high enough above saturation that the initial state can be treated as an ideal gas. Equally clearly, the initial gas pressures are far too high (order 20,000 MPa) to be of value. Space must be made available in the reactor chamber for free expansion to tolerable transient pressures, perhaps 30-40 MPa. This requires a volume expansion ratio of 3000-4000. For a 13 cm radius lithium sphere (2000 MJ fusion yield), with a 5 m high reactor chamber, the lithium fall must be at a 1.5 m radius from the centerline.

FIG. 4-8. Radius to saturated vapor in lithium sphere as a function of fusion energy yield.

The fraction of neutron energy that goes into forming the gas ball can be found from

$$E_{gas} = \int_0^{r_v} \epsilon \, dV$$

which, after using Eqs. (1) and (2) gives

$$\frac{E_{gas}}{E_n} \approx 1 - e^{-r_v/\lambda}$$

This is shown as a function of yield in Fig. 4-10. Also shown in the figure is the ratio of total gas energy to total fusion energy. The increase is from the initial 37% of the fusion energy in the form of X-rays and target debris which also goes to heat the gas. Note that nearly 80% of the fusion energy can go into forming this very hot gas ball at high fusion yields. These yields are also shown in terms of tons of TNT equivalent. The practicality of such high yields is obviously in question.

FIG. 4-9. Average energy, temperature, and pressure in lithium gas ball as a function of fusion yield.

No work is produced during the free expansion to lower pressure. The gas temperature therefore changes little (none at all for a truly ideal gas). Once the gas fills the reactor chamber, it begins to do work on the lithium fall, accelerating it into the turbine. The net efficiency, defined as the ratio of turbine work out to fusion energy in, is

$$\eta_{net} \equiv \frac{W}{E_{fus}}$$

$$= \frac{\eta_T}{E_{gas}} \frac{W'}{E_{fus}} \frac{E_{gas}}{\eta_c} \quad (3)$$

where η_T is the turbine adiabatic efficiency which, for reasons discussed in the next section, is taken to be 0.80. W'/E_{gas} is the ratio of isentropic work out to gas energy in. This depends upon expansion ratio and for an ideal gas is just the Carnot efficiency:

FIG. 4-10. Cumulative fraction of energy in gas ball, showing effect of total fusion energy.

$$\frac{W'}{E_{gas}} = 1 - \left(\frac{V_1}{V_2} \right)^{k-1} = 1 - \frac{T_2}{T_1} = \eta_c$$

Figure 4-11 gives the range of W'/E_{gas} for two gasses. A value of 1.6 corresponds to a monatomic gas like lithium while 1.4 would apply to a diatomic gas like air. This is a positive displacement expander much like an auto engine. Total expander volume is a function of expansion ratio. To hold reactor chamber volume to reasonable levels, we have adopted an expansion ratio of 16. Ideally, then, 81% of the gas energy can be converted to kinetic energy of the fall.

FIG. 4-11. Work out for isentropic ideal gas expansion for two gasses. Lithium has $k = 1.6$.

Some adjustment is required to account for the nonideal effects of phase transformation and variable heat capacity. We include for this the ratio η/η_c . In more conventional power cycles, this ratio varies from 0.5 for a simple moderate temperature Brayton cycle

to 0.78 for a multiple reheat Rankine cycle. We should note that this is simply a heat engine: it is just that. Heat has been added to a substance to raise its pressure, which is the effect of momentum of random atomic motions, so that it can expand and do PV work on the surroundings. The initial directed energy becomes randomized. This cycle is therefore Carnot-limited, and so we must include the real world factor η/η_c . Without further analysis, we have picked it to be 0.75, near the high end of the scale.

Figure 4-12 shows the estimated net overall efficiency as defined by Eq. (3) as a function of fusion yield. Clearly, after all effects are accounted for, the only advantage over a conventional thermal cycle is that the hot lithium leaving the turbine can be recycled to a bottoming cycle for further energy extraction. Of course, the question is whether this added complexity is justified. Complete power balances, with and without the lithium sphere, are discussed in Section 4.5.

The time required to expand and cool the lithium gas sphere is expected to be several milliseconds.^[4-1] There may be time for some of the gas ball energy to radiate away. Assuming infinite thermal conductivity in the gas ball, the energy balance is given by

$$\rho V C_p \frac{dT}{dt} = -\epsilon A \sigma T^4$$

This is plotted in Fig. 4-13 for a 13 cm radius gas sphere initially at 3.3 eV for two emissivities, 0.1 and 1.0. The former also applies to an emissivity of 1.0 and a wall reflectivity of 0.9. In the worst case, temperature falls to about 1.0 eV in about 150 msec. This simple calculation agrees remarkably well with a more detailed calculation.^[4-6] Because the expansion time is several millisecc, only a small fraction of energy is lost before the fall is accelerated.

In summary, we have explored the option of putting a close-in lithium sphere around the fusion target. The sphere would be room temperature except for a central tube holding the target, which would be at 20 K. The energy required to chill this tube would be about one percent of the fusion output. The sphere would be sized so that all of it

FIG. 4-12. Net conversion efficiencies for Turbostar case with lithium sphere sized out to saturated vapor.

vaporized, creating a very high pressure gas that would first isothermally expand down to a structurally reasonable pressure and then expand against the lithium fall. This fall would be accelerated into a turbine. While it is possible to convert 60–70% of the fusion energy into lithium vapor, the net efficiency after considering all factors turns out to be only 30–40%. This would slightly lower because a small portion of the energy in the hot gas will radiate to the surface of the lithium fall during expansion. The overall power balances with this approach will be examined in detail in Section 4.5.

FIG. 4-13. Radiation loss rate from 13 cm lithium gas ball assuming gas is perfect conductor.

4.4. EFFECT OF PULSATING FLOW ON TURBINE

ICF reactors are inherently pulsed while turbines function best at steady speed. There is therefore the question of the allowable velocity swing that can be tolerated before turbine efficiency degrades excessively. In the analysis below, we consider for simplicity a simple impulse turbine where the fluid is accelerated through stationary nozzles. The turbine blades merely turn the flow with no change in flow speed. Turbine blades that accelerate the flow further are called reaction turbines. Although they are a little more efficient, more stages are required. Figure 4-14 shows the nozzle and blade arrangement and the velocity diagram for impulse blading. The nozzle turns the flow so that it is almost, but not quite, tangential.

The moving blades turn the flow such that the relative jet velocity, V_{jr} , leaving the blades is a mirror of that entering. By following the vector diagram, one sees that the blade

FIG. 4-14. Nozzle and blade arrangement and velocity diagram for impulse turbine.

tip speed is subtracted from the jet velocity twice. Energy is extracted from the stream by this momentum transfer. The maximum energy transfer occurs when the exhaust velocity is minimum, which is when it is exactly axial. If V_{jet} is too high or too low, a tangential exhaust component will also exist, lowering efficiency.

The efficiency is defined by

$$\eta = 1 - \left(\frac{V_{exh}}{V_{jet}} \right)^2 \quad (4)$$

The axial and tangential components of the initial jet velocity are given by

$$V_{ja} = V_{jet} \sin \theta$$

$$V_{jt} = V_{jet} \cos \theta \quad (5)$$

and the tangential component of exhaust velocity is

$$V_{et} = V_{jt} - 2 V_{tip} \quad (6)$$

The exhaust velocity is then

$$V_{exh} = \sqrt{V_{et}^2 + V_{ja}^2} \quad (7)$$

V_{tip} , V_{jet} , and θ are known. Substituting Eqs. (5)–(7) into Eq. (4) and simplifying yields

$$\eta = 4 \frac{V_{tip}}{V_{jet}} \left(\cos \theta - \frac{V_{tip}}{V_{jet}} \right)$$

This is plotted in Fig. 4-15 for two nozzle angles. Peak efficiency occurs when the turbine tip speed is about half the jet speed (it would be exactly half with zero nozzle angle). Of interest is what happens when jet speed varies by a factor of two. If done properly, as seen in the figure, efficiency falls off only about 10–12 percent at the extreme. Over a time average, the efficiency loss is only about 5–6%. Ignoring frictional losses, then, we would expect average efficiencies of about 90% for a 10 degree nozzle angle and 85% for 20 degrees. Friction and turbulence can be expected to cause about a ten point reduction in efficiency with impulse blades.^[4–7] We therefore cannot expect overall efficiencies over about 80% for 10 degree nozzle angle, and less for higher angles. This 80% figure has been used in the efficiency estimates discussed in Section 4.3.

Pitts (Ref. 4-8) has suggested using multiple turbines at different tip speeds with the fluid stream free falling through different arcs depending on flow velocity. While indeed a clever idea, a quick inspection shows that, with the high jet velocity (over 300 m/sec – Ref. 4-1), the arc would be very shallow, resulting in large overall nuclear island diameters, and entrance effects from the (for the turbines) pulsed flow would produce losses similar to that from the cycling velocities discussed above.

FIG. 4-15. Effect on turbine efficiency of gas velocity variation ignoring viscous and turbulence losses.

4.5. POWER BALANCES

In this section we evaluate power flows for the direct recovery methods discussed above and compare them with a conventional thermal cycle. Three cases are examined:

1. Turbostar with bare target and with bottoming cycle,
2. Turbostar with the target surrounded by a lithium sphere and with a bottoming cycle,
3. A vapor turbine system where the vaporized lithium is diluted to a temperature suitable for a turbine.

4.5.1. Turbostar with Bare Target

The power flow for a Turbostar configuration without the lithium sphere but with a bottoming cycle is shown in Fig. 4-16. The numbers are normalized to the total fusion energy. X-ray and debris energy constitute 37% of the total fusion energy corresponding to a target compression to $\rho r = 5 \text{ gm/cm}^2$ (Ref. 4-1). We assume an axial loss fraction of 1.0% for the X-ray and debris energy and 2.0 for the neutrons. We also assume a 2.0% pumping power fraction to circulate the liquid lithium. Presumably, good design would keep these values to these levels or below.

FIG. 4-16. Turbostar with bare target and thermal bottoming cycle.

The remaining 36% of the X-ray and debris energy interacts with the lithium fall by thermal radiation and sputtering to sublime a substantial amount of lithium, increasing the mass of the gas in the chamber and lowering its temperature until thermal radiation ceases to have an influence (Ref. 4-1). This gas undergoes an adiabatic expansion which

accelerates the remaining lithium in the fall. According to Ref. 4-1, 64% of the gas energy is converted to lithium fall kinetic energy. The gas presumably condenses and its residual thermal energy contributes to that going to the bottoming cycle. The fall kinetic energy is extracted by a hydraulic turbine which, based on the discussion in the last section, has an assumed time-average conversion efficiency of 0.80. The bottoming thermal conversion systems are assumed to have an efficiency of 42%, typical of moderate temperature steam systems. The thermal only system is assumed to be 45% efficient, also state of the art. It is taken to be a little higher because it should be possible to have better high temperature control of the liquid lithium without the added complexity of direct conversion.

Referring to Fig. 4-16, the Turbostar conversion system directly converts 16% of the fusion power to electricity while the bottoming cycle converts 33% given a total conversion efficiency of 49%. This will be compared later to the other Turbostar configurations and to a simple thermal system.

4.5.2. Turbostar with Li-Sphere

The effect of a close-in lithium sphere is shown in Fig. 4-17. The sphere is sized so that all of it vaporizes. Therefore, 58% of the total fusion energy goes into the lithium gas ball. As shown in Fig. 4-12, about 30% of that is converted into fall kinetic energy. With an 80% average turbine efficiency, and after allowing for axial losses, 27% of the fusion energy makes it through the turbine. After subtracting the pump loss, the amount of fusion energy converted directly is increased to 25% from 16% for the bare target. After thermal conversion of the remainder in a bottoming cycle, net efficiency is increased from 49% with the bare target to 54%.

4.5.3. Turbine System with Mass Injection

As shown above, the Turbostar system with bottoming cycles yields net efficiencies marginally higher than a simple thermal conversion system. We therefore explored an alternate direct conversion embodiment which uses the close-in lithium sphere concept as before. However, instead of accelerating a lithium fall into a turbine, mass is added to the

FIG. 4-17. Turbostar with close-in lithium sphere and with thermal bottoming cycle.

gas in the reaction chamber to lower its temperature to a level suitable for direct injection into a vapor turbine.

We assume that the gas must be reduced to 1200°C for material compatibility. This is in the range of exotic alloys such as Hastelloy-C and is also acceptable for ceramics. We consider two diluents: lithium and sodium. Sodium is considered because, as will be shown, it has higher efficiency potential. Figures 4-18 and 4-19 show possible adiabatic expansions for lithium and sodium, respectively. The size and cost of the turbine depends in large part on the number of stages and on the exhaust pressure. If this pressure is very low, then the blade height for the last stage is large. Steam turbines generally exhaust at 0.5–2 psia. We extend this here down to 0.1 psia in order to make a point: With 1200°C maximum temperature, an expansion down to 0.1 psia will be in the two-phase region.

The exhaust temperature will therefore be 840°C regardless of inlet pressure. The Carnot efficiency is

$$\eta_c = \frac{1200 - 840}{1200 + 273} = 0.24$$

We can expect only about 75% of this, or 18%. Conventional steam cycles beat this by more than a factor of two.

As seen in Fig. 4-19, sodium fairs a little better. Expanding from 1200°C down to 0.1 psia takes the vapor down to 500°C, giving a Carnot efficiency of 48%. We would expect 75% of this, or 36%, still not as high as steam but close.

One can argue at this point that the lower efficiency pays off because it is a direct cycle and eliminates the high temperature heater. True, but it also introduces a hot liquid metal vapor turbine which will be very large because of the inherently low pressures need to keep the liquid phase fraction below 13%. Experience with steam has shown that more liquid will seriously erode the turbine blades. The same argument also does not allow for the cost of a lithium-sodium separation system.

A power balance for the direct injection system is shown in Fig. 4-20. For illustrative purposes, we pick a generic conversion efficiency of 30%. As before, the inclusion of the lithium sphere converts 60% of the fusion energy to gas energy. Fifteen percent of the fusion energy is converted directly and 34% thermally giving a total conversion efficiency of 49%, the same as all the others.

4.5.4. Comparison with Thermal Cycle

We now compare the approaches above with a simple thermal cycle. Power conversion efficiency here is taken to be 45%, typical of steam plants in existence for the past 30 years. In the combined cycles above, it was taken to be a little lower, 42%, in deference to the expansion taking place in the hydraulic turbine and to the difficulty in achieving uniformly high temperatures. The reactor is taken to be a simple lithium fall with a thermal

FIG. 4-18. Enthalpy - entropy diagram for lithium vapor showing possible adiabatic expansions through a turbine.

separation system that cycles the hot liquid metal to the steam generator. Figure 4-21 shows the power balance for the thermal cycle. Net efficiency is 42%, seven points lower than the others. It is doubtful that the added complexity of the others is therefore justified.

FIG. 4-19. Enthalpy - entropy diagram for sodium vapor showing possible adiabatic expansions through a turbine.

4.5.5. Summary

The results for the four cases above are summarized in Fig. 4-22. Contributions for direct and thermal bottoming cycles are shown. Our original criteria of at least 70% fusion energy recovery was not met in any of the cases. Similarly, our criteria of system simplification at nominal efficiencies does not appear to have been met either. Even if one

FIG. 4-20. Power flow for direct turbine injection.

FIG. 4-21. Power flow for simple lithium fall and thermal conversion system.

postulates that direct conversion alone without the bottoming cycle constitutes a valuable simplification, it is clear from the figure that conversion efficiencies are then too low. With a net efficiency of 42%, the thermal cycle would have 0.78 times the electrical output of the best, the lithium sphere concept, for the same thermal power. It must therefore cost 0.78 times as much for the same electricity cost or have 1/0.78 times higher availability. The lithium sphere concept has questionable feasibility because of poor driver access to the target.

FIG. 4-22. Summary of power balance results for two Turbostar configurations, a direct turbine injection system, and a simple thermal system.

If a larger driver angle is required, as is likely, then performance will suffer. We must therefore also compare the thermal system to the runners-up, both of which gave 49% net efficiency. The thermal system produces 0.86 times the electricity as these and so cost must be in proportion or availability in inverse proportion. Without devoting excessive time to a detailed study, we intuitively expect the thermal system to satisfy these requirements considering the added complexity and development requirements of the "direct" recovery systems examined. To be worth further consideration, such novel concepts must surely offer more than a 14-22% improvement over well-proven thermal systems.

4.6. OTHER CONSIDERATIONS

We have concentrated mainly on thermodynamic considerations in the course of this study. However, other issues did emerge that were not addressed but should at least be mentioned for completeness.

In a simple lithium fall configuration such as Hylife,^[4-9] where only thermal conversion is used, the reactor chamber remains under vacuum. The small amount of pressure buildup due to lithium vapor is rapidly dissipated or pumped away. In Turbostar, the reactor chamber is a high-pressure vessel, and a pulsed one at that. One must expect this to introduce difficult engineering challenges.

The placement of turbines, etc. in the nuclear island area is bound to lead to difficulty because of the substantial penetrating power of neutrons, which will lead to activation and remote handling. We believe it is better to keep the nuclear island as simple as possible, placing complex equipment in remote, maintainable locations far from any sources of activation.

As discussed in Ref. 4-1, the basic concept of direct recovery begins to make some sense when the non-neutron fraction of fusion power dominates, as it does with D-D, other alternate fusion fuels, and, possibly, with ICF fission-fusion. It may be worth exploring this alternative at a later time when the physics indicates that such fuels are attractive.

4.7. CONCLUSIONS

We have explored the Turbostar concept suggested by LLNL with emphasis on efficiency. The concept was studied both with a bare D-T fusion target and with a target surrounded by a solid lithium sphere sized such that it vaporized completely. The added energy deposition in the sphere from neutrons greatly increased the directed energy fraction. We also examined a non-Turbostar configuration using the lithium sphere with which more mass was added to lower the vaporized sphere temperature to a level suitable for advanced turbine materials. Finally, we compared the above with a simple lithium fall using a thermal conversion system.

In view of the relatively good performance of existing thermal systems, over 45%, the evaluation criteria was rather stringent: at least 70% conversion of the fusion energy or significant reactor simplification at normal efficiencies.

In all cases, the Turbostar concept and its direct injection derivative failed to meet these criteria. Bottoming cycles were required to obtain net efficiencies over 25%. Yet, even with this added complexity, net efficiencies of only 49-54% were achieved, too small in increment over the 42% possible with a conventional thermal system to justify the added complexity.

Rather than expend effort on direct recovery, it is recommended that advanced thermal systems be investigated. High temperature Brayton and Field cycles^[4-3] can achieve efficiencies of 50-55% with less development requirements than any of the direct conversion schemes investigated in this study.

5. OTHER POSSIBILITIES

In this section we briefly explore another reactor option that evolved as a sideline to the exploration of Turbostar and the other innovative concepts. The ideas are obviously quite sketchy and require substantial analysis.

During this study, we came to realize that it is important to keep the nuclear island area as simple as possible. We also learned that thermal conversion systems are hard to beat. The main problems with thermal conversions typically lie in the high temperature, high pressure heat exchangers. A solution to this problem, discussed below, is the Field cycle, which can operate at pressures low enough for pressure balanced heat exchangers, yet give high efficiency. This cycle, which is a hybrid Rankine/Brayton cycle using steam, was originally explored during the Cascade study^[5-1] and has been considerably refined since.

In addition to Cascade, the Hylife reactor concept^[5-2] is an example of the well-conceived ICF reactor embodiment. It has free-falling lithium falls that flow to a thermal conversion. The reactor itself is not pressurized. A possible variation of Hylife is shown in Fig. 5-1. Instead of gravity feed as in Hylife, the flow is upward with the velocity chosen somewhat independent of gravity. A turning channel at the top redirects the flow downward. The same flow channel then doubles upon itself, reducing the thickness required of the main stream for neutron attenuation. A target explosion would drive the stream outward into deflectors that turn it downward into the return stream and dissipate kinetic energy through turbulence. Splashing is deflected away from the central bore, which must be kept clear, by the initial stream.

FIG. 5-1. Upward flowing lithium fall reactor.

If velocity is high enough, the stream can be turned around more than once, and also the reactor can be placed with the axis horizontal. Figure 5-2 shows an example of this. The main advantage of having the axis horizontal is the ease in placement of the distant first mirrors. The deflection due to the ballistic path is actually quite small once the stream velocity reaches about 80 m/sec. For example, at that speed, with a reactor length of 8.0 m, the vertical deflection is only 5 cm. The total time needed to reestablish all four

FIG. 5-2. Multipass liquid lithium reactor with horizontal axis.
Top: Side view. Bottom: axial view.

streams is 0.4 sec, allowing a rep rate of 2.5 Hz. During the time the stream is flowing intact between shots, the kinetic energy generated by accelerating the stream through the annular nozzle can be largely recovered by an annular diffuser. When the stream integrity is destroyed by the target explosion, deflectors can direct the radial outflow around the outer casing to a sump at the bottom.

The low density of lithium helps to keep loads due to jet impact tolerable. For example, at 80 m/sec, the stagnation pressure is only 1.6 MPa. It should be possible to design small structural elements, such as turning vanes, to withstand these loads. Isochoric heating introduces other velocities whose loads must also be considered.

For high conversion efficiency, the hot portions of liquid metal may have to be separated from the cold portions and sent to the thermal conversion. Whether this is required or not depends on the flow rates and the fusion power level. If required, a means of doing this is shown in Fig. 5-3 where an active hot well containing a thermal sensor controls an active deflector vane that steers the flow according to its temperature. Not shown are the accumulators that would be required to minimize pressure surges.

The hot stream would pass to a pressurizer pump that matches the stream pressure to the steam pressure in the heater. For complete pressure balancing, the IHX fluid is also at that pressure. The heat exchanger tubes can then be sized for short term fault loads, where one side is momentarily depressurized. Design allowables for short term are typically 10 times that for long term creep, so that tube wall thickness can be made much less and relatively expensive alloys can be used because their total mass and cost are low. This of course is contingent on having creep loading dominate over fatigue. The orifice at the other end of the lithium stream provides the depressurization needed to bring it back to a level suitable for the reactor. This could also be a hydraulic motor to recovery some of that energy.

The Field cycle mentioned earlier is shown in the temperature entropy plane in Fig. 5-4. It is a hybrid system where the high pressure side acts like a Brayton cycle

FIG. 5-3. Active hot well to direct lithium flow and pressure-balanced heat exchangers.

with regeneration and vapor compression while the low pressure side acts like a Rankine cycle with extractions for feedwater heating and heat rejection by condensing steam. The main advantages are lower peak pressure, which facilitates pressure balancing of the heater and allows the use of higher steam temperature, and higher condensing temperature, which eases siting requirements and reduces the dimensions of the low pressure turbine.

Table 5-1 shows some of the cycle parameters. Note that 50% net efficiency is obtained with only 1100 K peak temperature. This is well within the range of many heat-resisting metal alloys. Overall pressure ratio is reduced from about 7000 for a conventional supercritical steam plant to about 1100. A six-stage compressor is required, which operates on

FIG. 5-4. The Field cycle.

the same shaft as the turbine. The feedpumps are low pressure, and consume about a third the power of those in conventional steam plants. Along with high pressure steam generators, these pumps are a common source of failure in conventional steam plants because of their high pressure and power levels. We would therefore expect the Field cycle to have high reliability.

TABLE 5-1
SOME FIELD CYCLE SPECS

Net Efficiency	0.500
Peak pressure	9.8 Mpa
Peak temperature	1100 K
Heater temperature rise	292 K
Condensing temperature	316 K
HPT pressure ratio	2.90
LPT pressure ratio	371
Compressor pressure ratio	3.02
Compressor inlet pressure	3.26 Mpa
Compressor discharge pressure	9.8 Mpa
Compressor discharge temperature	600 K
Regen low side pressure	3.26 Mpa
Regen high side pressure	9.8 Mpa
Regenerator effectiveness	.92
Peak regen temperature	808 K
Max feedwater pressure	7.5 Mpa
Feedpump power for 500 MW(e)	4.4 MW
Main steam flow for 500 MW(e)	1387 kg/sec

The Field cycle is a twentieth century cycle^[5-3] while both the Brayton and Rankine are from the nineteenth. It represents a good balance of both and makes a good transition cycle to the pure Brayton cycle which requires very high temperature materials for high efficiency.

6. SUMMARY AND CONCLUSIONS

Despite the initial appeal, it is concluded that direct mechanical recovery of fusion energy is not as practical as thermal cycles for ICF reactors. Note that this does not preclude exploring magnetic or electrostatic recovery, which may not be Carnot limited. Most importantly, we found that ideas that simplify the expensive nuclear island area are the most cost effective and practical and should be pursued. Key results are summarized below.

6.1. CASCADE ISSUES

The Cascade issues addressed in this study were (1) possible combustion of the carbon surface granule layer, (2) exploration of alternate granule materials, (3) the effect of reducing the carbon surface layer mass flow rate, and (4) cost estimates.

Even if combustion were to occur between the carbon surface layer and air that entered due to a leak, the pressure rise would be too small to eject solid particles into the immediate environment and temperatures from combustion would be too low to vaporize the lithium aluminate, the only component with any significant radioactivity. If the helium heat exchangers remained intact, they could remove the heat from combustion. If not, the vented helium from the power conversion secondary loop would purge out the air and combustion would cease.

We explored two alternate granule combinations: (1) a Be metal surface layer with a LiAlO_2 blanket and (2) a $\text{SiC}/\text{Li}_2\text{O}$ system. The first is unsuitable because Be metal can take only 1/25 the thermal stress as the original carbon first layer, and therefore must be placed much further from the target. The second is appealing because of its low activity. However, even though the dissociation products of SiC have low vapor pressure,

they would likely recondense separately. While some recombination may occur, it is likely that coatings of carbon and silicon would build up. How deleterious this is remains to be seen.

Returning to the original Cascade blanket with a carbon first layer, a reduction in carbon flow rate from $2.2 \text{ m}^3/\text{sec}$ to $1.0 \text{ m}^3/\text{sec}$ would require a 53% increase in carbon heat exchanger surface area resulting in a 0.3% increase in plant cost. However, because the helium pumping power is cut in half, the increased electricity made available for sale effectively cancels this increased capital cost.

Many details of the Cascade costing are discussed in this report. Emphasis was on cost reductions by exploiting the low activity in the nuclear island which allows many components to be non-nuclear grade.

6.2. ICF INNOVATIVE CONCEPTS

The purpose of this study was to explore ways of directly recovering by mechanical means the non-neutron energy from a fusion target with at least 70% conversion efficiency or in such a way that significant system simplifications and cost reductions were realized. Four concepts were examined: (1) an ablation turbine where the X-ray and debris energy caused blowoff impulse from the wetted surface of close-in turbine blades, (2) a liquid piston which uses a wetted wall that is vaporized by the target explosion and a free lithium surface that is driven downward into a hydraulic turbine, (3) a wave generator that was to exploit the wave action in a rotating hollow cylinder of liquid lithium, and (4) a resonant pump that was intended to build a series of small target energy pulses into a larger amplitude pulse from which hydraulic head energy could be more efficiently extracted.

The ablation turbine showed very poor conversion efficiencies. This was due to the extreme thinness of the blowoff gas layer. Most of the energy remained in this gas rather than the blade and it was realistically not possible to recover it through multiple bounces off of opposing turbine blades. The liquid piston, while potentially quite efficient, turned out to be large, unwieldy, and had low repetition rate. The wave generator could not store

the target energy in a wave of reasonable height. Finally, it was not possible to extract energy from the resonant pump without destroying the resonance. In summary, none of the concepts were feasible or showed any improvement over conventional energy conversion systems.

6.3. TURBOSTAR

The Turbostar concept, suggested by LLNL, was examined with a bare target, and with a target surrounded by a solid lithium sphere that vaporized completely. The purpose of the latter was to increase the amount of energy that could be converted directly by exploiting some of the neutron energy in addition to the X-ray and debris energy. The lithium sphere concept was also explored in a non-Turbostar configuration where mass was added to bring the temperature down to the point where it could be injected directly into a gas turbine.

These were compared with a conventional thermal system such as the Hylife reactor design. Without a bottoming thermal cycle, they all had much lower net efficiencies. With a bottoming cycle, efficiencies were only slightly higher, certainly not enough to justify the added nuclear island complexity. For example, the best was the Turbostar with the lithium sphere around the target. With a bottoming cycle, net efficiency was 54%, compared to 42% for the thermal cycle. Without the bottoming cycle, that efficiency dropped to 25%. While these performance numbers may seem impressive, they do not even approach our goal of achieving a significant efficiency gain (70% or more) or simplification of the reactor plant. The conventional thermal systems appear to be the better approach.

6.4. CONCLUSIONS

Thermal power conversion systems are hard to beat. Conventional steam systems have upwards of 45% efficiency. Advanced steam systems such as the Field cycle should be capable of 50% with conventional heat resisting alloys. And Brayton cycles with ceramic components should yield upwards of 60%. No method was found in this study to improve upon these values with innovative direct mechanical recovery techniques.

Direct recovery is possible for only 30-40% of the fusion energy. The rest is in the form of energetic neutrons and must be recovered thermally. Some type of thermal cycle, which adds complexity, is therefore always required. Furthermore, we examined direct recovery by vaporizing liquid lithium to drive lithium directly through a turbine. But this is also a thermal cycle, and is subject to the same Carnot limitations.

This program has taught us a great deal about how to evaluate fusion energy conversion ideas. Further, investigating new ideas and then documenting the results even if negative should help prevent others from exploring the same blind alleys in the future.

7. REFERENCES

- [1-1] I. Maya, K.R. Schultz, and Project Staff, "Inertial Confinement Fusion Reaction Chamber and Power Conversion System Study," GA Technologies Report GA-A17267, September 1984.
- [1-2] I. Maya, K.R. Schultz, and Project Staff, "Inertial Confinement Fusion Reaction Chamber and Power Conversion Study," GA Technologies Report GA-A17842, October 1985.
- [1-3] J.H. Pitts, "Turbostar, An ICF Reactor Using Both Direct and Thermal Power Conversion," Lawrence Livermore National Laboratory UCRL-93859 presented at the 7th Topical ANS Annual Meeting, Reno, Nevada, June 1986.
- [1-4] J.A. Blink, *et al.*, "The High-Yield Lithium-Injection Fusion-Energy (HYLIFE) Reactor," Lawrence Livermore National Laboratory UCRL-53559, December 23, 1985.
- [2-1] I. Maya, *et al.*, (Ref. 1-1.)
- [2-2] I. Maya, *et al.*, (Ref. 1-2.)
- [2-3] T. Baumeister, Ed., **Marks' Standard Handbook for Mechanical Engineers**, eighth ed., 1978.
- [2-4] G.J. Van Wylen and R.E. Sonntag, **Fundamentals of Classical Thermodynamics**, John Wiley and Sons, 1973.
- [2-5] **Handbook of Chemistry and Physics**, 50th ed., p. B-123.
- [2-6] Kirk-Othmer, **Encyclopedia of Chemical Technology**, 2nd ed., v. 3, New York, Interscience Publishers, 1964.
- [2-7] H.S. Carslaw and J.C. Jaeger, **Conduction of Heat in Solids**, 2nd ed., Oxford, Clarendon Press, 1959.
- [2-8] L. Waganer, McDonnell Douglas Astronautics Co., personal communication to K. Schultz, GA Technologies, April 1986.
- [3-1] J.A. Pitts (Ref. 1-3.)

- [3-2] A.J.C. Ladd, "Condensation of Ablated First-Wall Materials in the Cascade Inertial Confinement Fusion Reactor," Lawrence Livermore National Laboratory UCRL-53697, December 18, 1985.
- [3-3] J.H. Pitts, Lawrence Livermore National Laboratory, personal communication, June 1986.
- [3-4] R.L. Creedon, GA Technologies, Inc., personal communication, May, 1986.
- [4-1] J.A. Pitts (Ref. 1-3.)
- [4-2] "Heat Balance Diagram, Maximum Expected Flow, Oil/Gas Fired, Units No. 6 and 7, Moss Landing Power Plant," Drawing 328211, Dept. of Engineering, Pacific Gas and Electric Company, San Francisco, CA, November 1965.
- [4-3] I. Maya, *et al.*, (Ref. 1-2.)
- [4-4] J. Purcell, GA Technologies, personal communication, June 1986.
- [4-5] L.A. Glenn and D.A. Young, "Dynamic Loading of the Structural Wall in a Lithium-Fuel Fusion Reactor," Nuclear Engineering and Design 54 (1979) 1-16.
- [4-6] J.H. Pitts, Lawrence Livermore National Laboratory, personal written communication, April 1986.
- [4-7] E.F. Church Jr., **Steam Turbines**, 3rd ed., McGraw-Hill (NY) 1950.
- [4-8] J.H. Pitts, Lawrence Livermore National Laboratory, personal oral communication, April 1986.
- [4-9] J.A. Blink, *et al.*, (Ref. 1-4.)
- [5-1] I. Maya, *et al.*, (Ref. 1-2.)
- [5-2] J.A. Blink, *et al.*, (Ref. 1-4.)
- [5-3] J.F. Field, "The Application of Gas-turbine Technique to Steam Power," Proc. I. Mech. Eng., 162 (1950).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.