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OVERVIEW OF

SYSTEMS REQUIREMENTS

FOR

IMPACT FUSION POWER

J. M. Williams, L. A. Booth, R. A. Krakowski

A. PURPOSE

The DOE is considering funding research on the impact fusion concept. The University of Washington and the Los Alamos Scientific Laboratory have been asked to evaluate impact fusion and to develop a set of criteria for assessing the potential of impact fusion for power production. The purpose of this paper is to outline key areas in which the impact fusion concept must prove feasibility.

Little research has been devoted toward developing impact fusion as a potential power-producing technology. Many uncertainties will need resolution before this concept can have practical value. When certain key subsystems of a conceptual impact fusion reactor are taken separately, the development of a viable solution to technophysical problems may seem possible. However, to reach the practical goal of economic power production, an integrated power system must be economically feasible from the practical engineering standpoint.

At this time the scientific feasibility of impact fusion is the primary question. For the purposes of this paper scientific feasibility is defined as the condition in which the thermonuclear energy yield from impact fusion is equal to or greater than the energy in the incident projectile. The main purpose of this workshop is to investigate if any concepts or approaches are sufficiently promising to conclude that an appropriate experimental program could prove the scientific feasibility of impact fusion. Even if the physics concept appears scientifically feasible, numerous technical/economic questions must be addressed. How does this physics concept compare to others such as laser fusion and particle beam fusion, etc.? Is research and development easier and/or less costly? What are the engineering problems of establishing a net energy balance? Can one attain an average power level at which significantly more power is produced than is required for accelerating projectiles? Is it possible to operate an impact fusion reactor reliably in a pulsed mode for a long period of time -- weeks, months, years? Is there any feasible target-projectile combination which can be economically produced?

These and numerous other questions are the topic of this paper. The primary interest is to provide a perspective on problems of engineering feasibility which, although too early to solve now, could ultimately negate or enhance any practical solution for Impact Fusion power. Considering the state-of-the-art of Impact Fusion, any attempt to define "Systems Requirements for Impact Fusion" is pretty risky business. Thus, the material presented here is elementary and conjecture, and is primarily intended to stimulate discussion in this workshop: to prepare a definitive statement at this point is premature.

B. DESCRIPTION OF AN IMPACT FUSION POWER SYSTEM

An impact fusion power system exhibits many of the characteristics of inertial confinement concepts. It must drive a D-T implosion of some suitable target, achieve sizable gains of ~ 30 or greater and subsequently contain and convert the energetic particles and debris to useful power. Since impact fusion is by nature a pulsed system, all components, power supplies, accelerator, vacuum system, containment system and thermal hydraulic systems must be designed to tolerate cyclic loads for many millions of cycles per year during their useful lifetime. The energy efficiency of these components must be sufficiently high to assure a cost-effective, net energy balance.

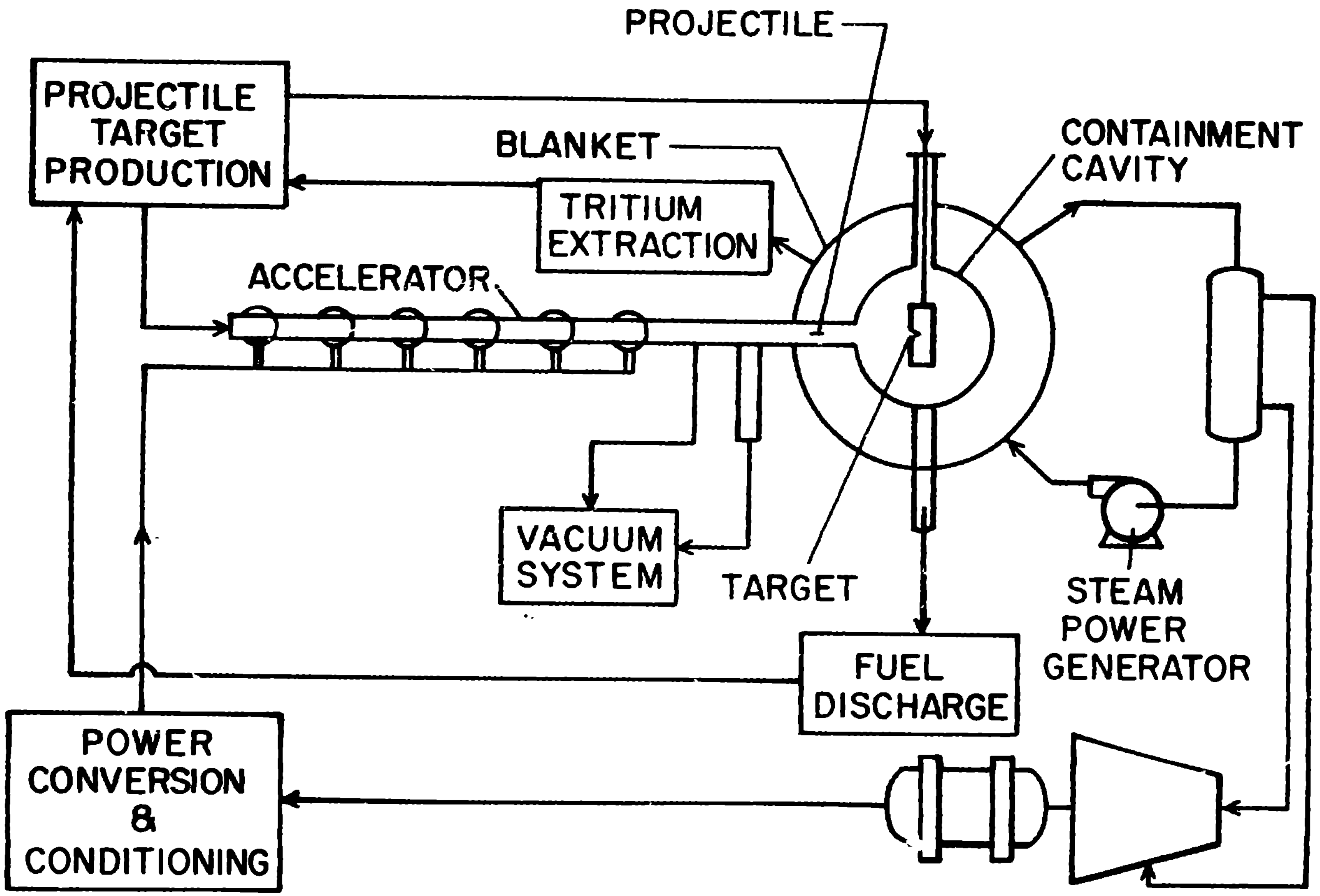
Figure 1 shows the key components in an impact fusion power system. Key subsystems and their functions are described below.

1. Power Conversion and Conditioning

   The power conversion and conditioning system will be required to utilize electrical energy from the power generation system and convert it into the proper pulse shape, current and voltages required to power the accelerator system. This function will probably require energy storage systems (e.g., capacitors and/or homopolar generators) and appropriate high-voltage switching gear. This equipment will have to operate in a pulsed mode at repetition rates in the range of 0.1 to 10 pulses per second. The total amount of energy to be provided to power conditioning systems in each pulse will probably range from 10 MJ to 1 GJ. Depending upon the time scale of the pulse characteristics from the power supply, there will be major requirements for development of hardware to satisfy this need. Much of the power conditioning hardware required for beam-driven fusion may be applicable here, but will probably require considerably more energy per pulse.

2. Projectile/target Production

   The purpose of this subsystem will be to produce complete projectile/target assemblies at a rate of at least one assembly every 10 s during the operating lifetime of this facility. This requirement would amount to approximately 2.5 million assemblies per year, if they are consumed at the rate of one every 10 seconds at an 80% duty factor. It is quite likely that these assemblies will require exotic materials, such as superconductors and high density refractories, which will have to be fabricated to close dimensional tolerances. In addition, the assembly that suspends the target in place will have to be partially replaced because it, in all liklihood, would be destroyed during each explosion. If the total energy yield from a single explosion is 10 GJ, then the value of an equivalent amount of electric energy produced at 3 ¢/kWe hour at the busbar would be approximately $25. Maybe 1/5 to 1/3 ($5-$8) of this revenue would be available for production of target projectile assemblies. This facility will have to be highly automated in order



KEY IMPACT FUSION COMPONENTS & SUBSYSTEMS

Fig. 1

achieve the required production rates. Possibly through proper economies of scale, it might be possible to produce reasonable cost assemblies. By degree, there is no counterpart to this system in beam-driven fusion although similar problems are encountered in the imploding liner in the magnetic fusion program.

3. Accelerator

The primary function of the accelerator will be to accelerate macroparticles or projectiles to velocities exceeding 10^7 cm/s. These projectiles may range in mass from 0.1 gm to as high as 1 kg. The accelerator will have to operate with reasonable conversion efficiencies for the conversion of electric to kinetic energy and must maintain a very stable trajectory targeted within close tolerances to impact on the target. This is probably one of the most challenging hardware development components in impact fusion. There are a number of accelerator concepts which may be promising; this workshop will evaluate each of them. There is no comparable technology currently under development in other fusion programs.

4. Containment Cavity

The primary purpose of the containment cavity is to provide an environment in which the target can receive the high velocity projectile and convert resulting fusion energy into useful thermal energy. The cavity must be capable of evacuation to an acceptable pressure such that the projectile does not overheat in traversing from the accelerator through a drift tube and across the radius of the cavity. The cavity must also be capable of absorbing the radiation and energetic particles that impact on the cavity first wall as well as thermalizing the energy deposited by 14-MeV neutrons in the coolant and structure of the blanket. Impact fusion containment concepts may be required to handle energy releases (in the form of x rays and ion debris) of up to 50 GJ. This energy is higher than for laser or magnetic fusion concepts. Containment technology has been studied extensively in the inertial confinement program and also in the fast-liner reactor studies. A number of conceptual approaches to energy containment will be discussed in greater detail in subsequent workshop papers.

5. Vacuum Systen: Cavity/Accelerator

Vacuum systems will be required to maintain the low pressure in both the accelerator and the containment cavity. This system will probably require high pumping speeds in order to minimize the debris that diffuses into the accelerator, and to prepare, on a short time scale (1-10 s), the cavity for the next explosion. Fast acting valves may be needed to separate the accelerator from the containment cavity between pulses. Vacuum system pumping capacity could be the primary limiting factor on the pulse repetition rate in the cavity. In view of the large quantity of debris from target projectile and supporting structure, the handling capacity of the vacuum system may be a severe engineering limitation.

Significant effort has been devoted to evaluation of vacuum system problems in both inertial confinement and magnetic fusion programs. From this work, it is clear that vacuum requirements can indirectly be a significant contributor to power system costs.

6. Blanket and Energy Conversion System

The blanket and energy conversion system serves the purpose of transferring radiation and particulate energies from the first wall to the coolant and accepting the energy from slowing down of 14-MeV neutrons in the coolant and structure to drive eventually the steam-generating system. The primary function of the blanket and energy conversion system is to convert the pulsed energy into steady state thermal power. This function requires a relatively large thermal sink to assure that thermal transients do not occur at the steam/electric generation system. The blanket design interacts closely with the containment cavity and must provide for effective containment, tritium breeding and cooling. Although this technology is unproven, various concepts have been under continuous study in the inertial and magnetic confinement programs for some time. Some concepts propose the combination of blast-containment, thermal-cooling, and tritium-breeding functions into a single system.

7. Tritium Breeding, Extraction and Recycle

Assuming that deuterium and tritium are the most likely fusion constituents, lithium will have to be used to generate tritium for maintaining the fusion fuel cycle. The blanket system must incorporate sufficient lithium in the system to breed net tritium for recycle. This function is normally done through use of lithium in the blanket and as a coolant; and is probably a reasonable way to proceed for impact fusion. Neutron economy for tritium breeding will be important, particularly if the target mass results in significant neutron degradation. Systems for extraction and recycle tritium have been adequately conceptualized and designed by other fusion programs, and this aspect is not a major technological problem for impact fusion.

8. Steam Power Generator

The steam power generator system serves the purpose of converting energy from the high-temperature lithium (or other) coolant into steam, which eventually drives a turbo-electric generator. This technology is well developed for other major systems applications and needs little additional discussion here.

C. CONCEPTUAL DESIGN PROBLEMS

Many of the subsystems discussed above appear conceptually feasible and significant development programs are underway in the magnetic and inertial fusion programs to solve these problems. The most crucial conceptual design problems for impact fusion are discussed below.

1. Accelerator Design and Performance

The accelerator must be designed to accelerate efficiently a complicated projectile to velocities of 10^7-10^8 cm/s. Two promising concepts for accomplishing this macroparticle velocity are the rail gun concept, which has demonstrated approximately 6 x 10^5 cm/s, and the traveling magnetic wave accelerator. Crucial system design parameters for the accelerator will be the power consumption per unit length, the total length of the accelerator, accelerator efficiency, and the stability of the traveling force front which drives the projectile.

It is desirable to design an accelerator of minimum length. A number of key accelerator-related questions can be formulated: design factors that limit the accelerator length; forces, stresses and heat loads on the projectile; maximum achievable magnetic field gradient; and spacing of driver coils around high-velocity end of accelerator.

Another aspect of accelerator system design is the question of proper projectile injection systems and (trajectory/energy) control systems to assure projectile stability during acceleration. It may be necessary to utilize pointing and tracking systems to assure that the target is properly positioned for impact. Other problems or system requirements may emerge as a result of further evaluations. Reasonable ranges for some of the design parameters might be as follows: accelerator efficiency, 30-90%; minimum projectile velocity, 10^7 cm/s; accelerator length, 2-3 km.

2. Accelerator/Projectile Coupling Constraints

Depending upon the accelerator concept proposed, the coupling of the accelerating force to the projectile will place major constraints on the overall system design. For example, in the case of the traveling magnetic wave accelerator, either a superconducting or ferromagnetic projectile is proposed. The projectile must have some minimum length in order to interact effectively with the accelerating magnetic field gradient. The total force on the projectile must not exceed stress limits in the projectile. Projectile heating or degradation of superconducting properties, resulting from electrical or magnetic effects, must also be minimized.

In addition to projectile/accelerator coupling constraints, consideration must be given to stability, oscillations of the magnetic field and eddy current heating of the projectile. The consequences of a projectile inadvertently running off course, particularly at the high energy end of the accelerator, presents another potential problem. Conceptual solutions to these problems are necessary in order to enhance the overall credibility of this concept.

3. Projectile Design and Performance

In addition to the projectile/accelerator/target coupling problems, the question arises of how a projectile can be designed to couple effectively with the accelerating field while at the same time being constructed in such a shape that its hydrodynamic interaction with the target makes maximum efficient use of the energy in the projectile. These two conflicting design constraints may be a very difficult problem for impact fusion.

It appears that minimum projectile velocities of 10^7 cm/s will be required when coupled with the more sophisticated target designs. At this velocity threshold complicated, expensive projectile target designs are likely to be necessary. If projectile velocities of 10^8 cm/s or greater are achievable, however, it appears that significantly simpler projectile/target designs may be possible at more acceptable costs.

Parameter values for this system might be as follows: projectile mass, 0.1 to 1000 gm; projectile energy, $> 10^7$ cm/s; and projectile/target cost, 30% net revenues.

4. Projectile/Target Coupling

Probably the most crucial question on the feasibility of impact fusion is associated with the means by which the linear kinetic energy in a projectile can be converted into implosive energy in an appropriate target. The simplest situation would be a planar shock and subsequent compression on a "fixed surface." Maximum shock compressions achievable is a factor of ~ 4 over normal D-T densities. Under these conditions the possibility of attaining sufficiently high values (fusion energy divided by projectile energy) before the compressed density is reduced below fusion conditions implies unacceptably high yields. Other techniques, such as pre-heating prior to compression, compression in cylindrical or spherical geometry, are probably necessary to achieve acceptable system gain factors at acceptable project velocities.

Many questions can be formulated on projectile/target design. How does linear kinetic energy transform into cylindrical or spherical implosive energy? How much kinetic energy is wasted?

Of course, these are the difficult, but important questions for this workshop. Numerous factors will affect the answers. Geometric matching is one factor that varies widely with design concept. The accuracy with which the projectile and target must match on impact to assure efficient implosive energy coupling may present stringent requirements. The target must be carefully positioned, and the projectile must be carefully guided and targeted. In some concepts, mismatches on the axis of impact and in the yaw of either target or projectile may have to be less than a micrometer of axis and a fraction of a degree in yaw in order to minimize energy dissipation and assure acceptable fusion yields and gains. Less sensitive designs may be possible at the expense of increased projectile velocity and/or energy.

The efficiency of coupling the projectile energy to implosive energy will probably have to be 5% or greater. This requirement, of course, depends upon overall energy balance considerations, but below 5% coupling efficiency D-T gain (Q) requirements rise rapidly.

Projectile/target design will also be a major factor in determining the quantity and complexity of materials destroyed by each blast. The integrated system design will need to remove and possibly reclaim these materials. Lastly, one must answer the question of what happens if the projectile misses the target? It would likely pass through the containment vessel wall.

5. Target Design and Performance

It may not be unreasonable to consider one *vs* two-sided impacts. Each approach has advantages and disadvantages. A two-sided impact has the primary advantage of being more symmetric and possibly easier accelerator and target design. However, accuracy requirements (particularly arrival time) for the increased trajectory are greater, two accelerators are needed, and the system becomes longer. Thus, there appears to exist a preference for a one-sided impact.

If the impact projectile comes from one side, then the target will have to be designed to assure that, in case of misfire, the linearly directed energy from the projectile does not damage the cavity. Other design considerations are important. What will be the final compressed geometry? How will this affect energy release and the distribution of energy in neutrons, alpha particles and debris? These uncertainties are important to assure tritium breeding and to evaluate blast effects on containment.

Other important design parameters are target mass, structure/geometry and degree of shock vs compressional heating. These parameters will all affect the cost of the projectile target assembly. The estimated budget for the complete assembly destroyed each shot will be a strong function of the overall energy balance parameters.

The system required for rapid target positioning and replacement will be important to overall system performance. To achieve maximum average power, the pulse repetition rate in each cavity must approach one to ten seconds per pulse for yields in the range of 10 GJ.

The main differences from other fusion concepts are that impact fusion will probably require higher yields per pulse and will produce large quantities of activated debris. These large quantities of materials will be circulated through the cavity, producing a large ex-reactor irradiated materials handling load.

6. Target/Containment Coupling

Although very important, this problem is possibly the least crucial to impact fusion feasibility of the problems that have been analyzed. Target/containment coupling is well understood in the magnetic fusion and inertial confinement applications at energy releases up to 10 GJ. Methods for minimizing detrimental blast effects of containment, such as wetted walls, lithium waterfalls, liquid-metal rains/sprays, etc., may provide adequate solutions to this problem. It should be noted, however, that an economical, viable, and integrated system must provide energy containment for millions of cycles per year in a radiation environment comprised of high energy neutrons, energetic alpha particles, γ rays and relatively massive debris. After each energy release the containment must attain a quiescent atmosphere into which the target and projectile can subsequently be injected within 1-10 s.

D. ENERGY BALANCES

Compared to other energy systems, fusion requires substantial investments in high quality energy to release net energy from the nuclear fusion reaction. The efficiency with which this high quality energy is handled therefore becomes one of the crucial analyses of fusion systems. A typical energy balance diagram is shown in Fig. 2. Analysis of the energy flows depicted in this diagram allows comparison of the key parameters in the energy balance. The key energy balance parameters for impact fusion which require understanding and significant development are.

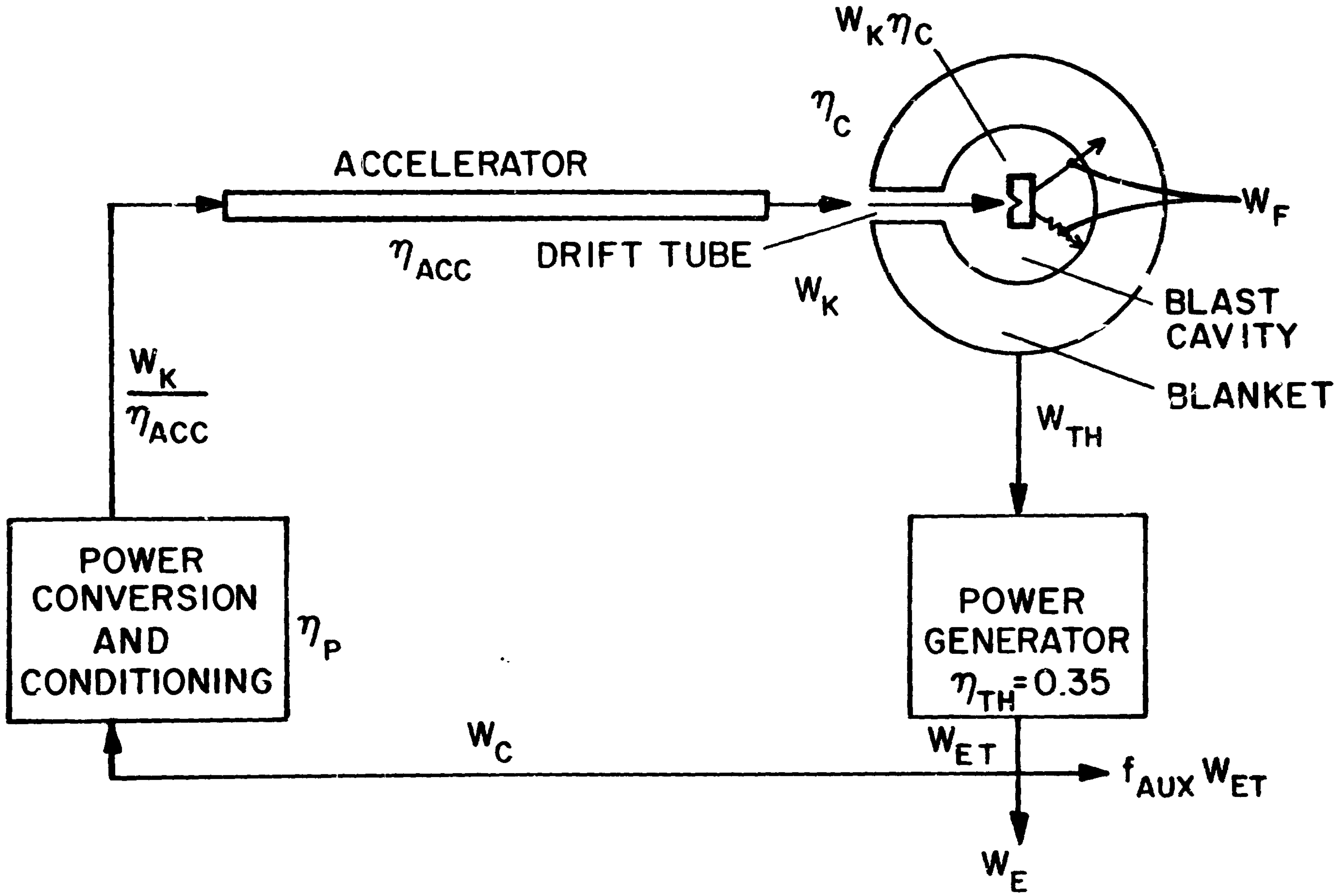
- The energy gain curve (Q <u>versus</u> projectile energy W_K) for the envelope of projectile/target designs, which includes understanding the mechanism for efficient conversion of projectile energy into implosion energy in an impact fusion target.
- The efficiency of converting electrical energy into accelerated projectile energy.

For the energy flow diagram (Fig. 2) the following energy balance relation can be derived:

$$Q_E = \frac{1}{\epsilon} = \frac{\eta_P \, \eta_{ACC} \, \eta_{TH}(1+Q)}{1 + f_{AUX} \, \eta_P \, \eta_{ACC} \, \eta_{TH}(1+Q)}$$

where, referring to Fig. 2:

Q_E	Engineering gain of system, W_{ET}/W_C
ϵ	Circulating power fraction W_C/W_{ET}
η_{ACC}	Acceleration efficiency
η_{TH}	Thermal-to-electric conversion efficiency
Q	Target/projectile gain
f_{AUX}	Fraction of auxiliary energy
η_P	Power conditioning efficiency



ENERGY BALANCE DIAGRAM

Fig. 2

Setting nominal values of $\eta_{TH} = 0.35$, $\eta_P = 1.0$, and $f_{AUX} = 0$, the functional relation between the accelerator efficiency, η_{ACC}, and system gain, Q, with circulating power, ε, as a parameter, can be determined. Figure 3 illustrates this relation. For a circulating power fraction greater than 0.3, the fraction of total capital cost that must be devoted to (parasitic) circulating power becomes large and the achievement of an economical system becomes increasingly more difficult.

For example, if the accelerator efficiency is 50%, the circulating power fraction is 0.2, a system gain factor of > 30 would be needed. On the other hand, if the accelerator efficiency is 0.5 and the circulating power fraction is 0.2, then the required system gain is > 70. If a smaller circulating power fraction is desirable or lower accelerator efficiencies more likely, the required target gain rises rapidly.

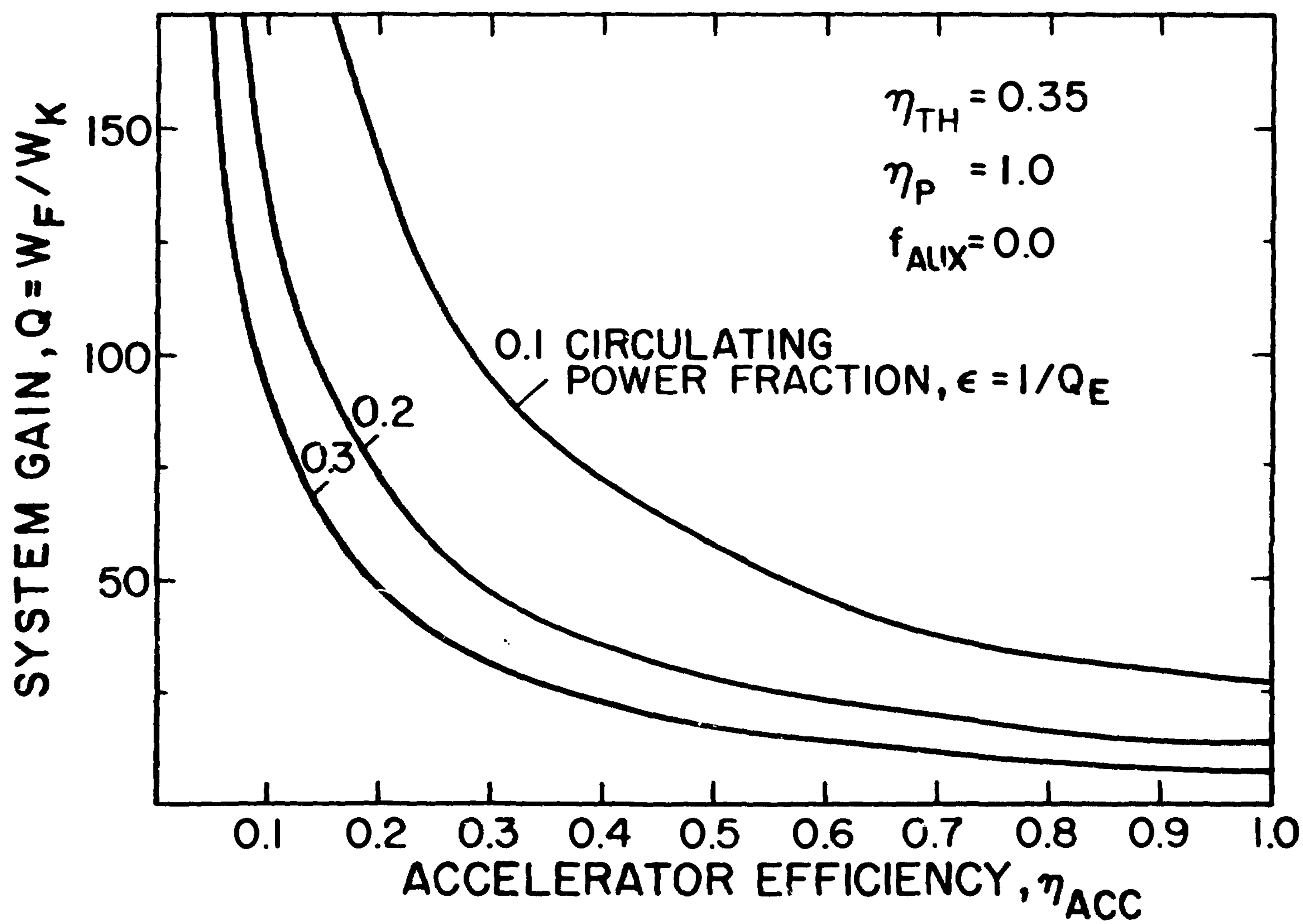
The consequences of a high-Q requirement on the overall system design/feasibility cannot be quantified until the gain curve (Q versus W_K) is known. The gain curve for a range of projectile/target configurations represents the most crucial unknown for impact fusion today, in that the requirements of both the accelerator and blast cavity are directly determined by this relationship between Q and W_K.

E. KEY SYSTEMS PARAMETERS

At this early state of our knowledge of impact fusion systems, it is useful to try to quantify key systems design parameters which will bound the region of acceptable conceptual design solutions. Five constraining parameters can be identified: minimum system gain, Q; maximum yield for practical containment, maximum practical projectile energy and velocity, minimum economical yield, $W_E = Q_{WK}$; and minimum acceptable projectile energy and velocity. The following is a rough rationale for how these parameters might be set. It is emphasized that the following development is intuitive and judgmental, and the conclusions and/or indications that follow from this development should be treated in this light.

1. Minimum System Gain

The minimum system gain is set by the energy balance just discussed. If we choose the following parameters: $\eta_{TH} = 0.35$, $\eta_P = 1.0$, $\eta_{ACC} = 0.5$, $1/Q_E = \varepsilon = 0.2$, and $f_{AUX} = 0.0$; it can be seen (Fig. 3)



ACCELERATOR EFFICIENCY vs SYSTEM GAIN TRADEOFF

Fig.3

that a gain of 30 is required. A minimum system gain of 30 is, therefore, chosen.

2. Maximum Yield for Practical Containment

Although it is a subjective conclusion at this point, experience in reactor design for inertial confinement and imploding liners provides a background for assessing practical limits on maximum containable yield. Conceptually there is some maximum limit on the radius of a practical containment vessel. This limit is set by the ability to construct large structures and to transport components or modules of that structure to the construction site. In addition, the reactor containment vessel must be capable of supporting itself while providing an evacuated volume where energy release takes place. Structural engineering considerations of such a vessel will set practical limits on size. The containment vessel must also be designed to accept energy pulses at the rate of once every 1 to 10 seconds for a lifetime as long as 10 to 30 years. Based on these considerations and more detailed analyses to be discussed (Krakowski, Booth and Bohachevsky), it seems optimistic to choose a maximum yield of $W_F \sim 100$ GJ, (~ 25 tonnes of TNT). Approximately 20-50% of this total fusion yield will contribute to the blast energy, depending upon the projectile/target interaction and design.

However, it is emphasized that cavity diameters are determined by both the wall protection method (bare metal walls would require uneconomically large diameters) and the energy form of pellet x ray and debris output, i.e., yield fractions, spectra, and temporal pulse widths. Furthermore, in all concepts except thick lithium fluidized walls, pulsed neutron damage may also be a major constraint in determining cavity diameter. Although an optimistic maximum yield of 100 GJ has been chosen, these considerations would result in significantly lower maximum yield, dependent upon wall protection method and pellet output characteristics unknown at this time.

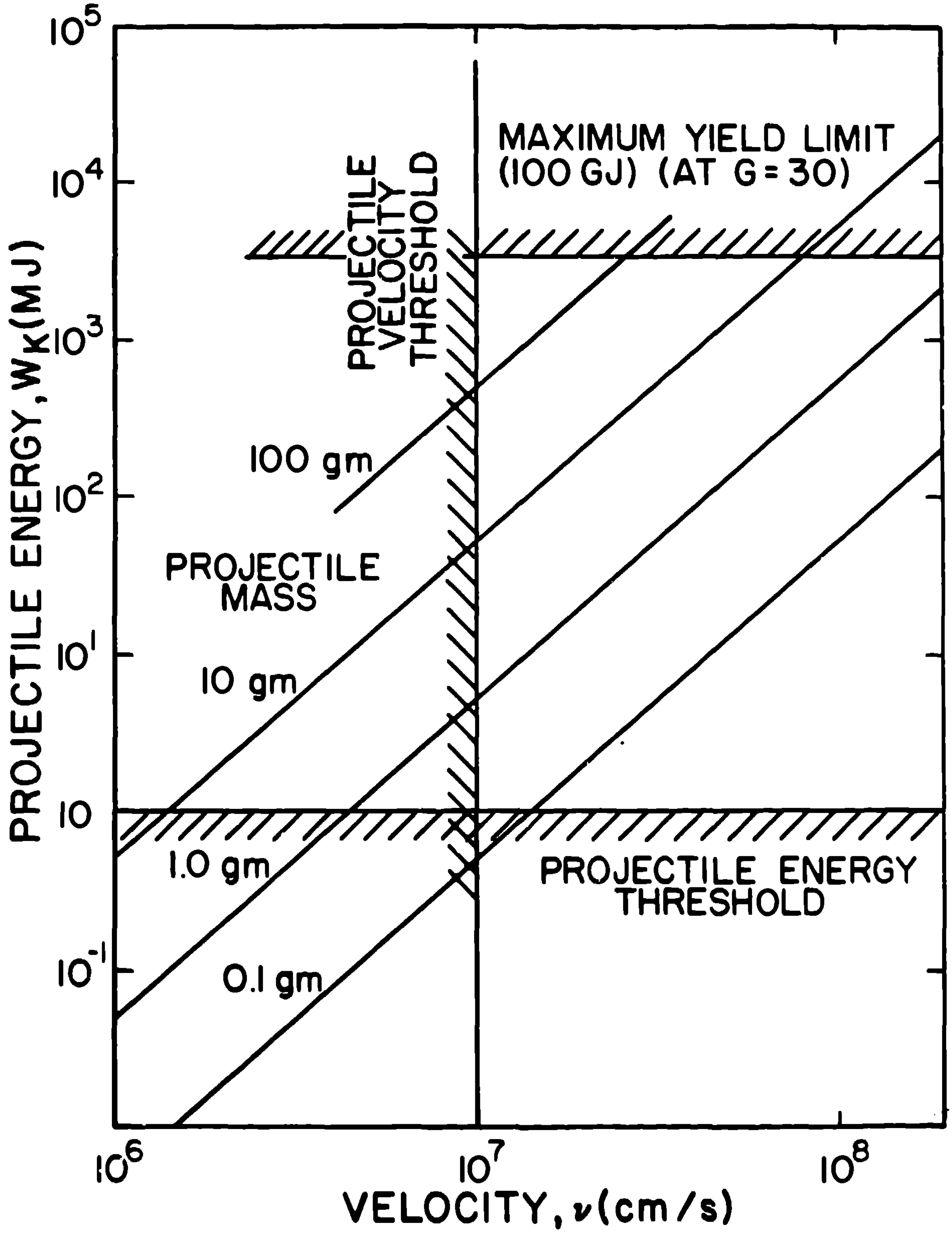
3. Maximum Practical Projectile Energy

The maximum practical projectile energy is set by the capability of the accelerator to achieve a maximum velocity for a given projectile configuration and mass. If the minimum gain of 30 and the maximum yield of 100 GJ is accepted, then the maximum acceptable projectile energy is approximately 3.3 GJ (Fig. 4). If larger gains are achieved within the maximum acceptable yield of 100 GJ, then the maximum projectile energy will be reduced. Therefore, a maximum projectile energy in the range of 1 GJ has been specified.

4. Minimum Economical Yield

The minimum economical yield is set by considerations of reasonable revenues resulting from power production and minimum reasonable power production rate of the reactor system. If the maximum pulse rate for an impact fusion reactor system is approximately 1 pulse every 10 seconds at a yield of 1 GJ per pulse, an equivalent average power level of 35 MW(e) will be produced by a single cavity. Multiple cavities for a single accelerator do not appear conceptually feasible at this time. Thirty-five megawatts of electrical energy would result in a revenue, at a busbar power cost of 3¢ a kWh, of 29¢ per second, or $2.90 per shot. The annual revenue at this rate is approximately $6.9 M per year. At a fixed charge rate of 15% per year, this would support a capital investment, neglecting fuel costs, of $50 M. If we allow $1 per shot for fuel production and for other operating and maintenance expenses, this $50 M reduces to an apportionment to capital investment of approximately $35 M. This is approximately equivalent to $1000/kW of installed capacity and compares favorably with current estimates for advanced electrical power systems.

Thus, the question becomes, "at what cost can each projectile/target assembly be manufactured?" If the fabrication and production problems of complex targets and projectiles are considered, as well as the insertion and positioning hardware which will all be destroyed each shot, it seems reasonable that the target/projectile assembly would easily cost $1 each. Thus, $\sim$ 1 GJ yield represents a reasonable estimate of minimum economical yield. Clearly, if more economical assemblies could be manufactured, the minimum economic yield would be reduced.



PROJECTILE ENERGY, MASS, VELOCITY RELATIONS

5. Minimum Projectile Energy

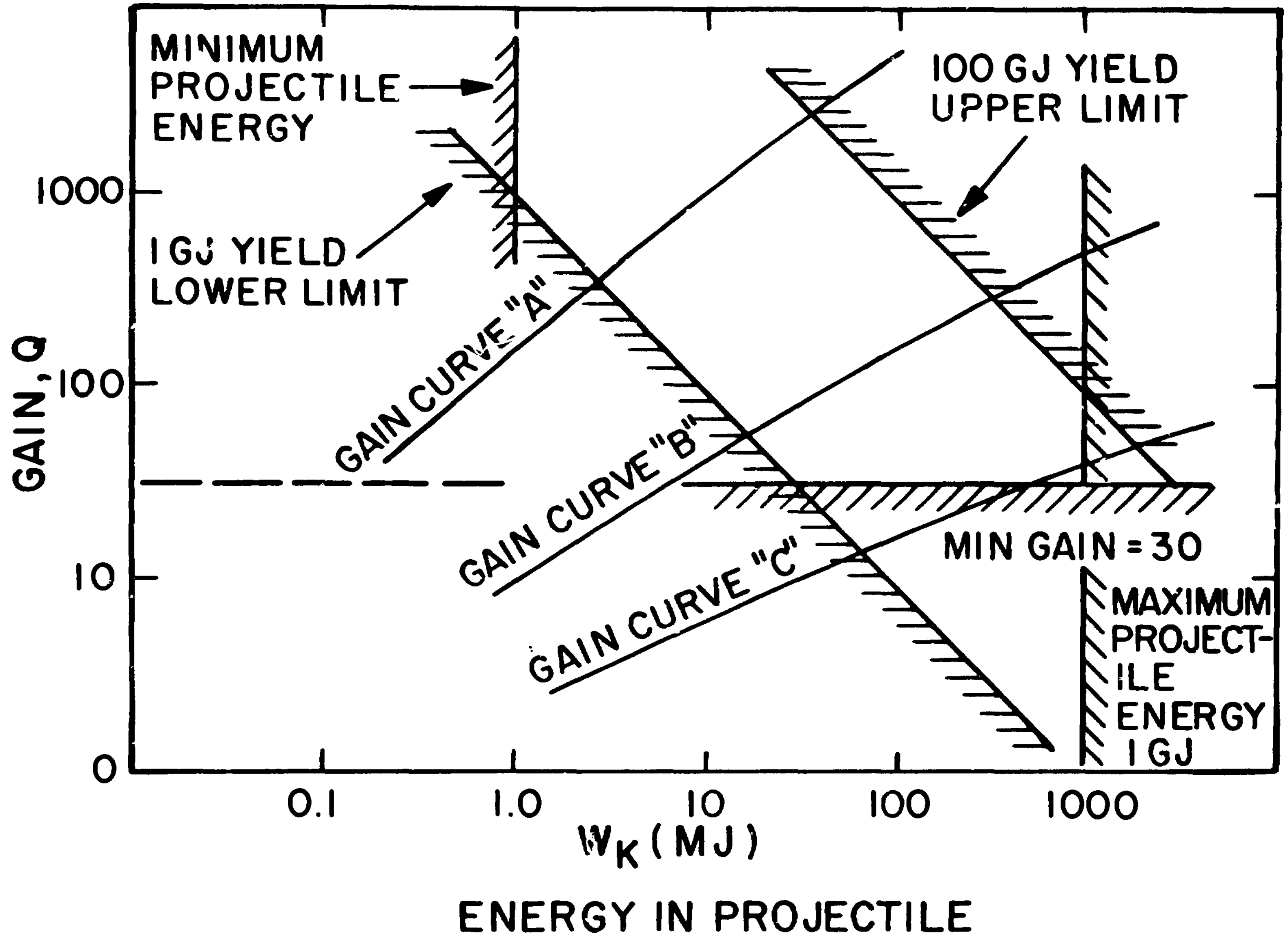
The minimum projectile energy will be set by the minimum acceptable velocity for impact fusion and the minimum mass which can be economically fabricated and efficiently accelerated. Consideration of the simplest target/projectile design led to the conclusion that a minimum velocity of 10^7 cm/s will be necessary. Numerous papers in this workshop will address that subject. At 10^7 cm/s, the projectile mass is slightly less than 0.2 gram for a 1 MJ projectile. The handling and manufacturing of millions of complex projectiles to high quality control specs which have a mass less than 0.2 of a gram may be very difficult. In addition, projectile energies less than a MJ are probably not likely to initiate significant fusion reactions via impact fusion approaches. Although these reasons are somewhat simple and specious, we have chosen 1 MG as a minimum reasonable projectile energy.

6. Summary of Key System Parameters

The following summarizes key systems parameters which bound the solutions:

Minimum System Gain	30
Maximum Yield for Practical Containment	100 GJ
Minimum Economical Yield	100 MJ
Maximum Practical Projectile Energy	1 GJ
Minimum Projectile Energy	1 MJ

If we accept these parameters, although, clearly, better values may be developed later as a result of more thorough analysis, the results can be presented as shown in Fig. 5 in terms of a Q versus W_K phase space. Figure 5 shows a set of three hypothetical gain curves which might result from different target projectile designs. Upon this gain curve we have superimposed the above-determined upper and lower bounds. From this visual representation, some insight can be gained into the required combination of systems performance parameters that must be achieved in order to obtain an "acceptable" solution to the impact fusion power concept.



LIMITING PARAMETERS FOR IMPACT FUSION

Fig. 5

F. CONCLUSIONS

The development of impact fusion power reactor concepts is very limited at this time. Key systems factors in arriving at practical concepts will be conception of credible systems and subsystems which promise an acceptable overall energy balance and development of target/projectile designs and gain versus projectile energy curves which allow system design tradeoffs to be accomplished. Important system parameters will be subsystem efficiencies (particularly the accelerator), target/projectile gain as a function of target design, circulating power fraction or engineering gain, system pulse repetition rate, size/cost scaling of components, containment cavity design limits, maximum yield, minimum economical yield, minimum projectile velocity and energy, and overall economics. When more detailed conceptual designs are available, then system tradeoffs and performance optimization will be possible.