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TITLE: COMPACT INERTIAL CONFINEMENT MULTIREACTOR CONCEPTS

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COMPACT INERTIAL CONFINEMENT FUSION MULTIREACTOR CONCEPTS

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ABSTRACT

Inertial confinement fusion (ICF) commercial-applications plant-optimum driver pulse repetition rates may exceed reactor pulse-repetition-rate capabilities. Thus, more than one reactor may be required for low-cost production of electric power, process heat, fissionable fuels, etc., in ICF plants. Substantial savings in expensive reactor containment cells and blankets can be realized by placing more than one reactor in a cell and by surrounding more than one reactor cavity with a single blanket system. There are also some potential disadvantages associated with close coupling in compact multicavity blankets and multireactor cells. Tradeoffs associated with several scenarios have been studied.

INTRODUCTION

In addition to environmental, safety, reliability, and plant scale considerations, two economic figures of merit used to compare ICF commercial-applications are prominent: (1) initial capital cost and (2) unit cost of production of electricity, process heat, fissionable fuels, etc. The second economic figure of merit correlates strongly with the first because capital charges are projected to dominate ICF economics. Cost savings can be obtained by technological breakthroughs that give better performance, allow less-expensive materials of construction and/or manufacturing methods to be used, etc. Simple ways to reduce the total amounts of concrete, pipe, wires, steel, insulation, shielding, etc., can have significant impacts on costs. We are concerned here with the latter class of cost-cutting techniques.

The costs of reactor containment cells and blankets (especially hybrid) and associated equipment typically are estimated to total to hundreds of millions of dollars for nominal 1000-MWe-net-electric ICF power generating stations. Thus, large savings on blankets and containment can have a significant impact on total plant cost. In "conventional" multireactor ICF plant concepts, each containment cell encloses but a single reactor and each blanket surrounds only one reactor cavity.[1] Large savings in reactor containment cell volume and wall, floor, and ceiling area and in blanket volume and surface area relative to conventional layouts can be obtained by placing more than one reactor in each reactor cell and by enclosing more than one reactor cavity in a single blanket system. These ideas are illustrated in Fig. 1.

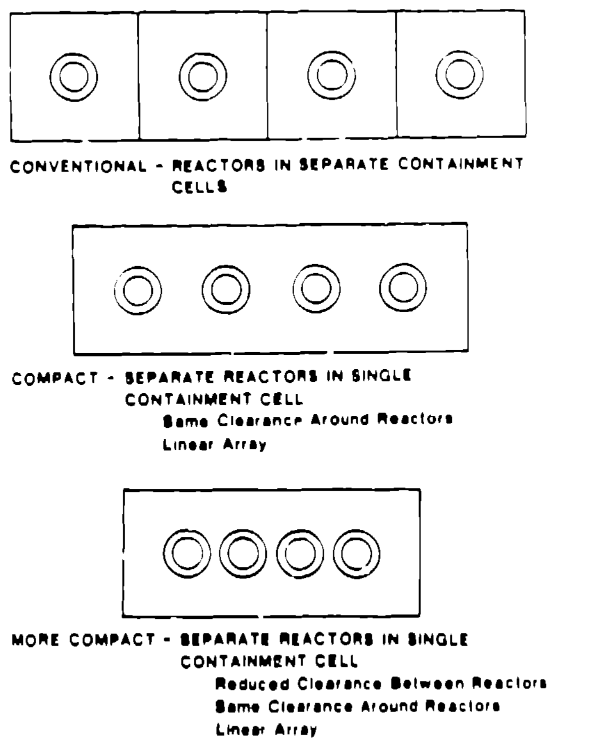
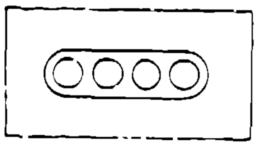


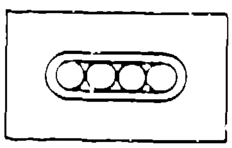
Fig. 1. Schematic of compact multireactor containment cell and multicavity blanket ICF concepts (continued on next page).

We see other potential advantages as well. Total piping, control-line, driver-beam-line, etc., runs can be reduced. The capacities of equipment required to maintain reactor cell environments can be reduced. Shielding can be smaller and leakage of radiation, hazardous chemicals, and dangerous isotopes can be reduced or control becomes easier. Switching of high-repetition-rate driver beams from one lower-repetition-rate reactor to another can be easier and less expensive, because beam deflection angles can be less and fewer beam turns may be feasible. This consideration is viewed as especially important for heavy-ion fusion because stiff ion beams must be transported in evacuated tubes and can only be turned using bulky, expensive, superconducting magnets with large turning radii. Required capacities for reactor plant equipment such as tritium recovery, safety, etc., systems depend in part on the volume of blankets. Finally, it may be possible to combine reactor subsystems when reactors are closely coupled to take obtain of economies of scale not feasible with conventional plant layouts.

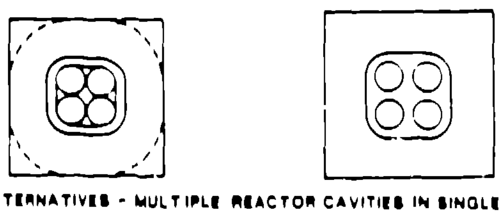
Conventional plant layouts also have potential advantages relative to the compact concepts considered here. Single-cell hazardous material inventories would be lower. Repair and/or routine maintenance of one reactor while others continue to operate may be feasible. Access for repair and maintenance may be better. Plant capacity reductions can be less in the event of unscheduled shutdown and/or catastrophic failure of one reactor if damage can be confined to its cell and the cell can be isolated from others without interfering with operation of other reactors. Finally, direct-drive targets, which require relatively uniform irradiation with many driver beams distributed more or less uniformly in solid angle, would be easier to accommodate with isolated reactors.*



EVEN MORE COMPACT - MULTIPLE REACTOR CAVITIES WITHIN SINGLE BLANKET SYSTEM IN SINGLE CONTAINMENT CELL
Linear Array
Full Blanket Between Cavities
Same Clearance Around Reactors



No Blanket Between Cavities



ALTERNATIVES - MULTIPLE REACTOR CAVITIES IN SINGLE CONTAINMENT CELL WITHIN SINGLE BLANKET SYSTEM
No Or Full Blanket Between Cavities
Cell Corners Square Or Rounded
Same Clearance Around Reactors
Planar Array

Fig. 1. Continued.

Direct-driver targets may still be accomodated in multireactor cells, but probably not with multicavity blankets. Multicavity blankets appear to offer no significant problems for the single-sided and double-sided irradiation of targets feasible with indirect-drive targets if only linear or planar arrays of cavities are considered. We have considered only such geometries in our studies. The relative merits of direct-drive targets, which have potential for higher gains than indirect-drive targets at the same driver pulse energy, but also greatly constrain reactor design options and may add substantially to final beam transport and focusing costs, are still being investigated.

It may be possible to obtain some of the advantages of the proposed compact schemes and yet retain some of the advantages of the conventional concepts. For example, better access for repair and maintenance could be provided by allowing for more clearance around reactors in multireactor cells. Continued operation of other reactors while a failed reactor is being repaired may be possible if better remote maintenance procedures are developed. Designs that prevent failure of one reactor from damaging or interfering with operation of adjacent reactors may be feasible. Even in cases where a single large reactor represents a good match to the driver, sufficiently inexpensive compact multicavity reactor concepts could permit reduced probability of loss of all plant capacity if one cavity fails. In particular, heavy-ion accelerators apparently can be competitive at lower gains, but higher pulse repetition rates, because they offer higher efficiencies and can be repetitively pulsed at very high rates for little additional cost.

The magnitudes of many of the potential benefits of compact multireactor containment cells and multicavity blankets will be reactor, driver, etc., concept-specific. Also the scope of the present study did not permit examination of all possible tradeoffs. Therefore, we confine our discussion here to relatively straightforward analysis of a few important generic aspects for a few different scenarios and additional discussion of some of the issues mentioned above. Our primary objective was to stimulate further discussion of the tradeoffs in an attempt to improve the attractiveness of ICF for commercial applications. We note in passing that the magnetic fusion community[3,4] and the fission power industry[5] has been forced recently to consider ways to reduce reactor sizes in an effort to remain competitive. At least one attempt has been made at developing a more-compact ICF multireactor plant concept.[6]

FULL, MINIMAL, NO, AND OPTIMAL BLANKET THICKNESS

The greatest savings in blanket volume and area through enclosure of more than one reactor cavity within a single blanket system result if adjacent cavities have no blanket between them. At the other extreme, the least savings result when the full blanket thickness is included between cavities. How small can the thickness of blanket between adjacent reactor cavities be made? Is some thickness intermediate between zero and full thickness optimal?

Definitive answers to these questions can only be obtained through more extensive analyses with specific reactor concepts. The critical question is whether high-energy neutrons released by a pellet microexplosion in one cavity will cause unacceptable upsets in the restoration of cavity conditions required for survivable target injection and final driver beam transport and focusing in adjacent cavities. Dry-wall reactor concepts seem most likely to be resistant to upset by target emissions from adjacent cavities.[7] We believe for ICF reactor concepts that employ liquid metals for first-wall protection that interferences between adjacent cavities can be reduced to acceptable levels through appropriate design.[7] With no blanket between adjacent cavities, structure directly between reactor cavities and other first-wall structure would likely have to be replaced two or more times as often unless special designs can reduce neutron damage rates. Dry-wall reactor first walls may require special cooling systems; concepts that use liquid metals for first-wall protection should not. We have computed savings in blanket volume and area for the extremes of full blanket thickness and no blanket to bound the savings.

PURE-FUSION AND HYBRID BLANKETS

Potential cost savings are expected to scale differently for pure fusion than for hybrid blankets. Tritium breeding materials and heat transport fluids that have been proposed for pure-fusion blankets are relatively inexpensive. For example, highly purified lithium presently costs a few tens of $/kg or a few tens of thousands of $/m³. Solid lithium compounds can be more or less expensive, depending on the compound. The cost of gaseous coolants, such as helium, is also modest.

Pure-fusion ICF reactor blanket structure is expected to be relatively simple, with few geometric constraints, and relatively inexpensive. Insulation, heat tracing, instrumentation, shielding, etc., will add substantially to the total cost. The significant pure-fusion blanket costs apparently scale approximately with blanket outer surface area. Required capacities for such blanket-related reactor plant equipment as tritium recovery and liquid-metal safety systems will depend somewhat on blanket volume.

The fertile-isotope-containing elements in hybrid ICF blankets, conventional clad pins in hexagonal cans for example, are relatively expensive. Approximate costs for complete hybrid blanket assemblies are often expressed in terms of contained heavy metal (HM), depend on element design, and typically fall in the few-hundred-$/kg HM range. With heavy-metal densities approaching 20,000 kg/m³ and volume fractions of heavy metal > 0.75, fertile blanket costs of a few million $/m³ are typical.

The great weight of hybrid blankets makes reactor support a much greater problem for them than for pure fusion. Other hybrid blanket structure and blanket-related reactor subsystems are expected to be similar to those for pure fusion. Hybrid blanket geometries are expected to be more constrained than those of pure-fusion blankets; conventional fuel pins in hexagonal cans cannot be readily accomodated in spherical-shell blankets. Hybrid-blanket costs are expected to scale more closely with blanket volume than with surface area. Because hybrid blankets are expected to be much more expensive than pure fusion blankets, savings in blanket volume are more important.

MULTICAVITY BLANKET VOLUME AND AREA SAVINGS

For the linear and planar compact multicavity ICF blanket geometries depicted schematically in Figs. 2, 3, and 4, we have computed the ratios of multicavity blanket volume and outer surface area to the corresponding totals for the same number of separate single-cavity blankets. The calculations were performed for the extremes of full blanket thickness and no blanket between adjacent reactor cavities. Blanket inner surface area and connecting blanket structure area is expected to be roughly proportional to blanket outer surface area.

The results for the geometry of Fig. 2 are graphed in Figs. 5 and 6. Results for the geometries of Fig. 3 are displayed graphically in Figs. 7 and 8. Space limitations preclude showing results for the geometries of Figs. 3 and 4,

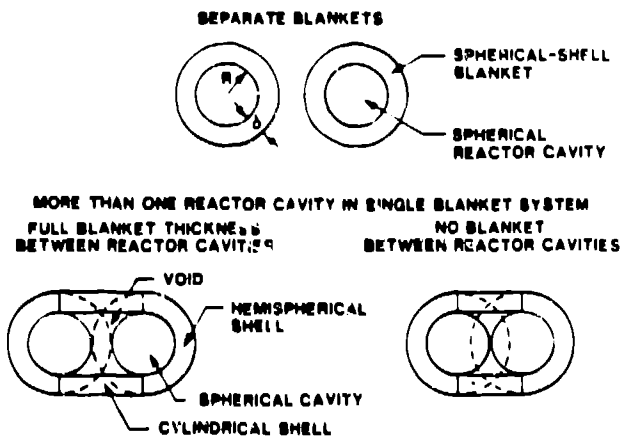


Fig. 2. Transformation of separate spherical reactor cavity/spherical-shell blanket combinations into linear multicavity cylindrical-shell/hemispherical-shell blanket concepts.

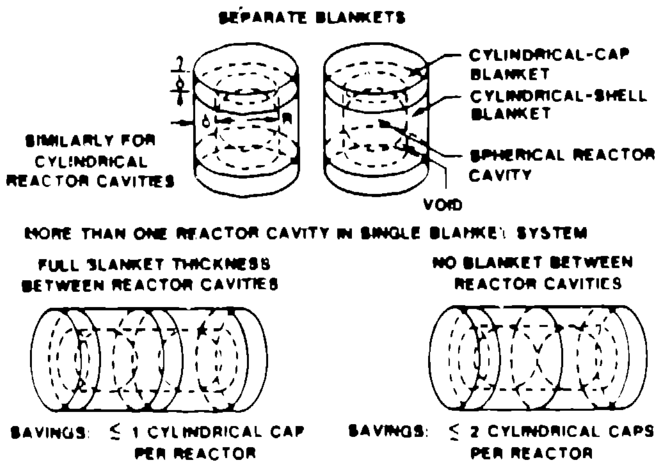


Fig. 3. Transformation of separate spherical (or cylindrical) reactor cavity/cylindrical-shell blanket combinations into linear multicavity cylindrical-shell blanket concepts.

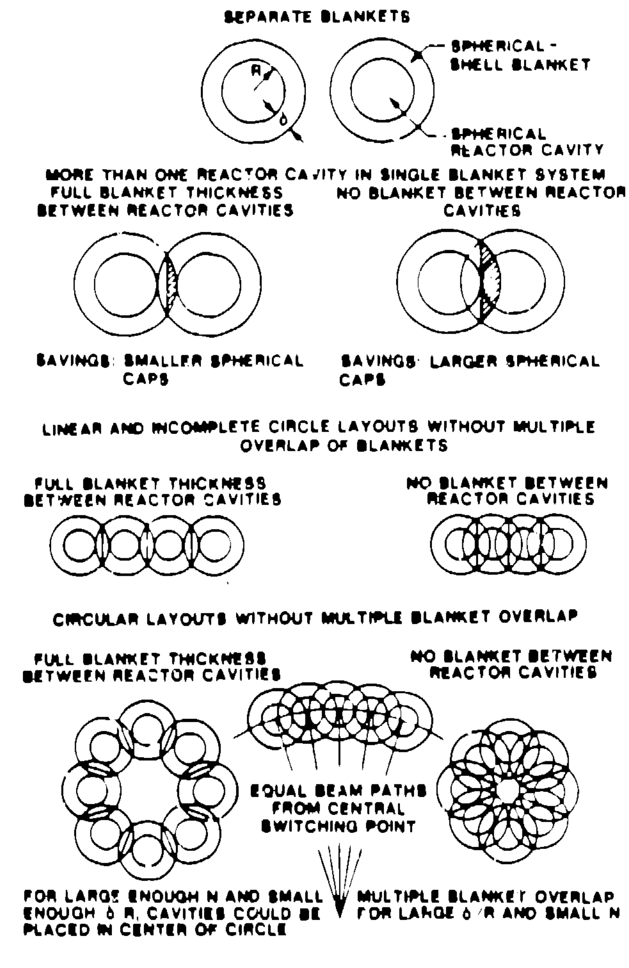


Fig. 4. Transformation of separate spherical reactor reactor cavity/spherical-shell blanket combinations into linear and circular multicavity spherical-shell blanket concepts.

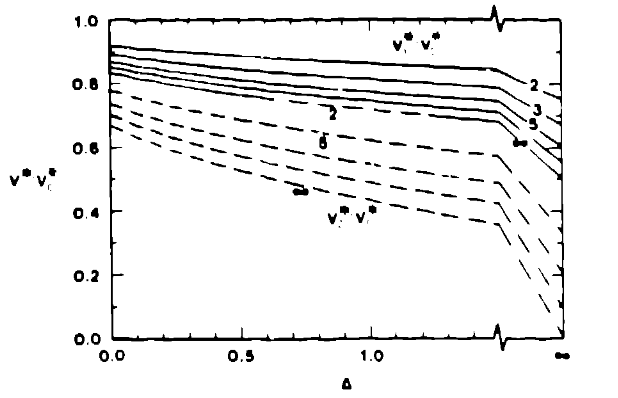


Fig. 5. Compact multicavity blanket concept total volume savings relative to conventional separate blankets (V_c^*/V_s^*) as function of reduced blanket thickness ($\Delta = \delta/R$) and number of reactor cavities (N) for the geometry of Fig. 2.

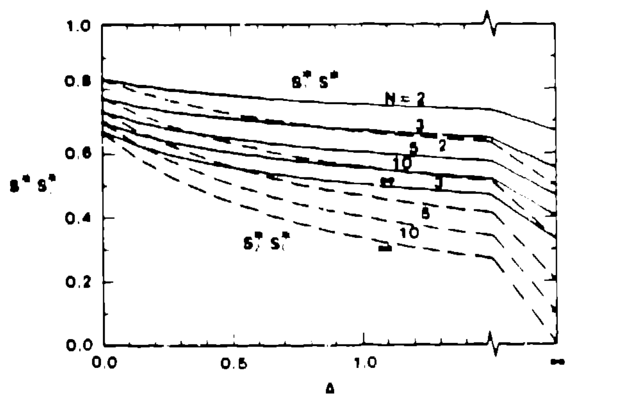


Fig. 6. Compact multicavity blanket concept total outer surface area savings relative to conventional separate blankets (S_c^*/S_s^*) for the geometry of Fig. 2.

but they are similar. In general, we expect blanket thickness to be around 1 m, although shielding, insulation, instrumentation, heat tracing, support structure, etc., can increase effective geometric blanket thicknesses somewhat. ICF reaction chamber radii are usually estimated to be a few m to over 10 m, depending on reactor concept. Thus, the ratio of blanket thickness to cavity radius is generally expected to be < 1. The infinite-Δ and infinite-N cases are included merely to indicate the ultimate bounds on possible savings in volume and area.

In general, what we see are interesting potential savings in blanket volume and area for the compact multicavity blanket concepts. For many scenarios, the choice of conventional or multicavity concept will probably be dictated by some of the other tradeoffs that we have discussed. Some otherwise attractive multicavity blanket geometries that may confer some of the advantages of other multicavity blanket concepts involve larger blanket volumes and areas. Enclosing all reactor cavities in a single blanket may appear to be a case of "putting all of one's eggs in one basket," with potentially adverse effects on reliability. However, fewer total penetrations, pipes, etc., will be required. These components frequently constitute "weak" points in power plants.

SINGLE-REACTOR VERSUS MULTIREACTOR CONTAINMENT CELLS

For some ICF reactor concepts (especially with laser drivers), high-energy, penetrating fusion neutron leakage into reactor cells may be great enough to necessitate thick (>1 m) containment cell walls, floors, and ceilings, special shielding and heat-removal systems to protect concrete, etc.. For reactor concepts that use liquid metals for tritium breeding and/or primary heat transport, inert-gas containment-cell atmospheres will probably be mandated for safety reasons. Thus, although ICF reactor containment requirements will be different from those for fission reactors, ICF containment cells will also be expensive and savings in containment cost through reductions in total containment requirements are potentially important. The cost of containment walls, floor, and ceiling and some other cell subsystems, such as special shielding, will scale roughly as area and other equipment, such as inert-gas equipment, will scale more with cell volume.

Containment cell volume and wall, floor, and ceiling area savings relative to single-reactor cell layouts for three multireactor-cell scenarios are summarized in Figs. 7 and 8. The three scenarios, all of which involve linear rectangular layouts and constant cell ceiling height above the cell floor, are (1) a multicavity blanket with full blanket thickness between cavities in a single containment cell and the same clearance around the reactor as in the single-reactor-cell case, (2) the same as (1) but with no blanket between adjacent cavities, and (3) a multireactor containment cell with separate blankets for each reactor and the same clearance around the reactors. These three types of cell layout are illustrated to scale in Fig. 1. The results presented in Figs. 9 and 10 are for only one representative value of reduced blanket thickness, but cover a wide range of reduced clearance around the reactors. Other options for which results could have been presented involve nonlinear layouts and rounded cell corners that conform with constant clearance to blanket contours. In general, we expect reduced clearances around reactors greater than one.

The results presented in Figs. 8 and 9 indicate that substantial cost savings may be possible through the use of multireactor containment cells. However, as was suggested for multicavity blanket concepts, other considerations may tip the balance toward either the conventional or the compact concepts.

SUMMARY

We have identified many potential ICF plant cost savings through the use of compact multireactor containment cells and multicavity blanket concepts. Some of these potential savings were investigated quantitatively for a few simple scenarios. Many interesting tradeoffs involving cost, reliability, safety, etc., considerations were discussed. We feel that many of the ideas presented in this paper deserve further study.

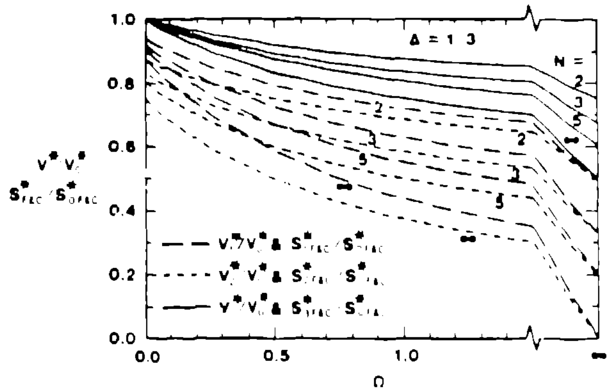


Fig. 8. Compact multireactor containment-cell concept total volume (V_c^*/V_s^*) and floor and ceiling area ($S_{c,f\&c}^*/S_{s,f\&c}^*$) savings relative to conventional single-reactor cells as functions of reduced clearance around reactors ($\Omega = \ell/[R + \delta]$) and number of reactor cavities (N) for a fixed representative value of reduced blanket thickness ($\Delta = \delta/R$).

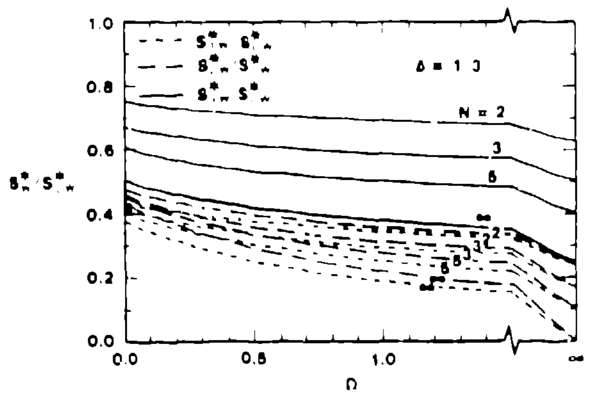


Fig. 9. Compact multireactor containment-cell total wall area ($S_{c,w}/S_{s,w}$) savings relative to conventional cells.

NOMENCLATURE

Parameters and Variables

δ = blanket thickness
ω = clearance around reactors
H = height of reactor containment cell
N = number of reactors or reactor cavities
R = radius of reactor cavity
S = blanket outer surface area
V = blanket volume
$\Delta = \delta/R$
$\Omega = \omega/(R + \delta)$

Subscripts and Superscripts

0 denotes separate reactor containment cells and blankets
1 denotes full blanket thickness between reactor cavities in multicavity blankets
2 denotes no blanket between reactor cavities in multicavity blankets
3 denotes separate reactor blankets in a single containment cell
F&C denotes containment cell floor and ceiling
W denotes containment cell walls
* denotes total for all reactor cavities

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