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STRUCTURE RENEWAL AND MAINTENANCE REQUIREMENTS IN A FUSION REACTOR

by

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ABSTRACT

The breeding blanket of a fusion reactor will be subjected to a fluence of neutrons of higher energy than has so far been obtained in reactor irradiations. It is unlikely that the effect of this radiation field, although to some extent predictable, will be fully demonstrated until a fusion reactor is built. This poses interesting problems for the reactor designer, some of which are discussed in this paper.

As was the case in the development of fission reactors, the first fusion reactor(s) will therefore be the test bed for the structural materials of the system. Pending the development of high-endurance materials which will retain adequate physical and mechanical properties throughout the economic life of a reactor, we must assume that routine replacement of the blanket structure will be a necessity. The probability of random failure of blanket structure is also very high owing to the severe environment, and the necessary repairs and replacement should be made possible without excessive disruption to reactor operation.

Therefore, in the belief that there will be a need for maintenance and structure renewal in a fusion reactor, an analysis is made of the nature of the problems arising. Examples are given based on familiar concepts, and assessments are made of their influence on the design and operation of fusion reactors.

It is concluded that a vital step in the design of practical fusion reactors will be provision (in spite of high activation levels) for demountability :-

1. In prototypes - to facilitate development by replacement and modification of the blanket structure.

2. In power reactors - to achieve low power costs.

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INTRODUCTION

1. Fusion reactors could be producing electrical power by the end of this century. If this dream is to become a reality we must move from our present position, where our thoughts are constrained to a large extent by the needs of the physics machines built to demonstrate control of thermonuclear fusion, to address ourselves to the problems of building a practical working reactor.

2. The key structural component of a fusion reactor is the breeding blanket surrounding the reacting plasma. This paper seeks to show how analysis of the working conditions to which the blanket will be subjected can lead to the formulation of important principles of design for the blanket structure. The material presented shows one aspect of recent United Kingdom studies of the technology of fusion reactors. It is also an extension of work by Mitchell and myself reported in Ref. (1).

There we considered a typical toroidal system with a circular cross-section of minimum diameter. We have now extended our analysis to include non-circular cross-sections and arrangements with space between the magnet-shield and blanket. In the course of our studies we have become aware of the profound significance of the requirements for maintenance of the blanket structure in the overall design of the plasma containment for fusion reactors.

THE STRUCTURAL CONCEPT OF A FUSION-REACTOR BLANKET

3. We must consider several factors in developing a structural concept for a fusion-reactor blanket. The most important are:

The functions of the blanket.

Its interrelation with other components of the plasma containment, e.g. the confining-magnetic-field windings.

Access for services, refuelling and maintenance.

The availability of suitable structural materials and their predictable endurance in the working environment of the blanket.

4. The limit of the blanket cross-section is determined over a large part (about 50%) of its surface by the windings for the confining magnetic field. Of possible magnet cross-sections we shall see later that a minimum-diameter circular one, although attractive for limiting magnet costs, appears to present insurmountable problems of maintenance. A larger-diameter magnet may be more expensive, but the greater space within its boundaries allows these

problems to be solved. A convenient shape is the "force-reduced," "D"-shaped magnet conceived at Princeton(2), which fortunately combines an attractive magnet design with good access to the blanket.

5. A "D"-shaped magnet layout (Fig. 1) has been used to illustrate many of the points in this paper. The principles derived are however applicable generally, and may be used to test the practicability of any blanket layout. Mitchell's cellular-blanket concept(1,3)(Fig. 2) has been retained and extended to allow a variety of cell shapes and integral groupings.

BLANKET FUNCTIONS

6. Taking the D-T reactor as our model, the energy of the thermonuclear reaction is emitted from the plasma as neutrons (80%) and Bremsstrahlung (2-5%). One function of the blanket is to trap this energy and convert it to heat for the generation of electricity. In so doing it has a secondary use in shielding the toroidal-field magnets from the flux of neutrons from the plasma. There will nevertheless be apertures in the blanket to allow for fuel supplies and plasma - ash removal as well as reactor instrumentation and control devices. The blanket must also breed tritium to maintain the reactor fuel supply, and for this purpose the blanket must contain lithium either as a metal or in a lithium-bearing fused salt. However, the depth of blanket for adequate tritium breeding is less than that required for full shielding of the superconducting magnets, so additional neutron-shielding is required between the blanket and the coils of the magnets.

7. An essential function of the blanket structure is to contain the liquid-metal or fused-salt blanket fluid. The integrity of this containment must be maintained, since loss of the fluid through a leak into the plasma chamber (probably detectable via the divertor output) would probably shut the reactor down by cooling the plasma and stopping the fusion reaction. Stopping the supply of lithium to the cell which was leaking and letting the remaining lithium in it leak away would not allow the reactor to continue to operate, because, unless as yet undefined measures could be taken, the locally uncooled structure would melt and the reflector and shielding would locally receive a greatly increased neutron flux. An inevitable consequence of a leak is therefore that it must be repaired before the penalties of continued operation become intolerable.

THE WORKING ENVIRONMENT OF BLANKET STRUCTURE

8. It has been suggested by many authors that the first wall, which is part of the blanket structure, could also form the boundary of the high-vacuum space containing the plasma. I believe that it is more probable that the main vacuum boundary will be formed in the magnet-shield, so the blanket, even if it forms an intermediate vacuum boundary, will be wholly within a vacuum space. Thus with a lithium- or lithium-salt-bearing blanket separated from a region of high vacuum by at least one wall of the blanket cells there will be a pressure problem, which will be greater or smaller depending on whether the lithium or lithium salt is passed through the blanket for cooling or merely circulated slowly for impurity control and tritium extraction. In the latter case the blanket would be cooled by, for instance, high-pressure gas passing through tubes inside the blanket, but the blanket structure would still be stressed by a pressure difference of at least 1 atmosphere across the cell walls.

9. The energy deposition in the structure will result in temperature gradients through the cell walls as the heat passes to the coolant. The temperature of the heat-transport medium (lithium, helium etc.) must rise by 200-400K in its passage through the blanket to around 850K to achieve a reasonable thermal efficiency for electricity generation from the energy absorbed in the blanket. The blanket structure will therefore be subjected to thermal stress and will operate at temperatures at which thermal creep would also be expected to occur.

10. The effect of the neutron bombardment will be to degrade the mechanical properties of the structural materials of the blanket and to cause dimensional changes arising from void growth. This irreversible effect could be the cause of mechanical interference between components. The surface of blanket structure exposed to the plasma chamber will also be subjected to erosion by particle bombardment.

THE LIFE OF BLANKET STRUCTURE

11. One of the following factors will surely limit the service life of the blanket structure:

Growth, by void formation,)
)
Loss of ductility)
)
Transmutation effects) due to neutron bombardment
)
Hydrogen embrittlement)
)
Radiation creep)

Thermal creep

Particle erosion on the plasma side of the blanket

Chemical corrosion by the blanket fluid.

Of these, transmutation effects, hydrogen embrittlement, and particle erosion are new problems peculiar to fusion reactors. The influence of these factors on the blanket design and performance will vary through the depth of the blanket with temperature, neutron flux, and neutron-flux spectrum.

12. On current evidence we cannot say which factor will impose the most severe limitation on blanket-structure life. However, of known structural materials, none appear likely to remain usable for 25 years (the minimum accountable life of a reactor) under the level of neutron bombardment in association with wall loadings. A long-life material could not be developed until some time after the building of prototype and early fusion reactors. We must therefore accept that initially there will be significant limitations to the performance of the candidate materials for fusion-reactor blanket structure, and in the foreseeable future there is little prospect that the endurance of blanket-structure materials will be more than a fraction of the accountable life of a reactor.

REQUIREMENTS FOR STRUCTURE RENEWAL

13. The fabrication of a blanket structure, whether as a single piece or as many thousands of individual cells, which will survive under the specified working conditions without the possibility of a leak in its working life is clearly inconceivable,and a leak could not be tolerated indefinitely. In any case the consequences of having to repair a leak after the structure has become activated, assuming one had not made specific provision for doing so, would be severe in terms of time, effort and money. I suggest therefore that fusion-reactor designers will have to provide for renewal of blanket structure as a routine procedure.

14. Random failure of blanket structure may occur at any time after the reactor is built, whereas renewal of parts damaged by radiation or corrosion would be required only at specific intervals of time. It could be argued that to provide for, say, irradiation-damage renewal one could arrange for a complete shutdown of the reactor every five years or one could remove large slices at shorter intervals.

15. The scale of such disassembly and reassembly operations is vast, requiring the breaking and remaking of tens of metres of high-vacuum seal and many liquid-metal circuits, together with the movement of hundreds of tons of equipment. The proving of vacuum and liquid-metal seals and the re-establishment of working conditions, high vacuum, large temperature differences and so on, is an almost unquantifiable task until it has been tried! I have attempted an analysis of these operations, and for routine renewal of a fifteen-segment reactor, assuming the time taken to change one segment does not exceed 30 days, the blanket-structure life must be at least 8½ years to achieve 85% availability (equivalent to say 75% load factor if allowance is made for miscellaneous low-power running). There would be two shutdowns per year.

16. If we also remember that we must provide for random failures and miscellaneous defects, the load factor is still lower. It is therefore logical to consider renewal of the blanket structure in smaller units or modules, such as would be appropriate to local repair of a leak. Preliminary analysis of this process for one of many possible combinations, a 10-day shutdown to change 30 modules (10 cells each), shows that 85% availability can be achieved with a structure life of only 6 years. There would be five shutdowns per year, and the additional loss of availability due to unscheduled shutdowns would be less significant than for segmental renewal. Subsequent analysis in this paper is on the basis of what we may call modular renewal, but allowance is made for the removal of a slice or segment of the reactor (Fig. 3), e.g. for replacement for a toroid-magnet coil.

CONSTRAINTS ON STRUCTURE RENEWAL

17. A practical system of structure renewal must satisfy a number of criteria, viz:

A high reactor load factor must be maintained.

Scarce or hazardous materials, e.g. lithium, tritium, refractory metals, must not be spilled or wasted.

The system should be automated wherever possible, particularly to avoid personal risk.

The system should be flexible in execution to allow for unforeseen events.

Mechanisms and procedure should be basically simple to reduce the risk of failures in service.

It should be possible to work on other parts of the system, e.g. magnetic-field windings, without excessive disruption of the main blanket-handling mechanism.

The overall objectives in the reactor design such as low cost, ease of maintenance, high availability, safety and reliability must be met in the blanket design.

18. The reactor sub-systems, e.g. lithium supply, reactor control, injectors, instrumentation etc., enter or pass through both shield and blanket regions. Their presence will affect the design of a considerable portion of the blanket and shield, with corresponding deviations from the otherwise uniform pattern of components.

ACCESSIBILITY OF THE BLANKET FOR RENEWAL

19. The blanket is surrounded by the magnet-shield, through which access must be obtained to renew the blanket. If the shield is right against the blanket, modular or even single-cell renewal offers no advantage over segmental renewal, since the corresponding section of the shielding must be removed for access to each piece of blanket and so the entire shield must be demountable. With adequate separation between the blanket and shield it is possible to obtain access through selected openings (Fig. 4) in the shield for manipulation of blanket modules, and this is an attractive arrangement if the magnet-shield also forms the main vacuum boundary. The shield apertures would be readily accessible for resealing after blanket-renewal operations, and the length of steel that would need to be cut and rewelded would be much less than in the case of segmental renewal.

DESIGNING A BLANKET FOR RENEWAL

20. Renewal of the blanket in the course of reactor operation requires a blanket structure that can be readily dismantled. If blanket modules are to be replaced one at a time then the structural stability of the blanket must be maintained, at least under shutdown conditions, with one or more

modules removed. The support structure for the blanket must therefore be arranged to correspond to the blanket modules or be integral with them. The blanket modules must be of a convenient size and weight and able to be handled by a machine which can work in the space between blanket and shield.

21. Removal of a blanket module requires its disconnection from lithium and/or other coolant supply ducts, instrumentation lines, etc. Breaking and remaking particularly the liquid-metal lines is clearly a difficult operation, and such operations must be kept to a minimum. There should therefore be only a single entry and exit for lithium or coolant to each blanket module with appropriate manifolding in the module to distribute the fluids (Fig. 5).

22. Handling techniques for blanket modules should as far as possible be straightforward and related to current practice in other systems. The most difficult part of the operation will be the breaking and sealing of liquid-metal supply and return lines and their subsequent reconnection after the insertion of a new module. The relatively high freezing point of lithium (186°C) should allow local solidification of the duct contents as an aid to sealing. Automated orbital cutting and welding techniques should be sufficiently common practice in 15-20 years time to allow their routine use in blanket renewal.

23. From the point of view of assembly and disassembly a straight cylindrical system is the least complicated. However the first fusion reactors are likely to be toroidal, and we should recognise the problems posed by toroidal geometry. If one could slice a torus up radially and remove the slices, the main problem would be the manipulation at the congested surfaces near the inside. However, this approach is uneconomic in terms of reactor operation, and the merits of a modular blanket system have been pointed out. In dealing with individual cells or modular groups of cells, we must take account of the fact that in order to form a continuous blanket, they are wedge-shaped in two planes at right angles, and at the inside of the torus the wedge angles are in opposition (Fig. 6). This means that withdrawal radially of a single cell is impossible on the inside of a torus. However, by grouping the cells in modules and arranging their shapes and groups of cells to include parallel planes of separation, it is possible to remove the modules without difficulty.

24. The blanket should preferably be so divided around the minor circumference as to achieve approximately equal volumes and thus equal weights for each module removed despite variations in shape. Apertures in the blanket for

fuel injection, plasma-ash removal, and reactor instrumentation and control devices should as far as possible be formed by the natural boundary of surrounding blanket cells (Fig. 7). If separate structural boundaries were provided to any of these passages they would require to be dismantled before blanket movement in their vicinity, thus increasing the handling time for blanket renewal.

25. The essential requirements in the design of a practical renewable blanket are as follows:

The ability to divide the blanket into easily handled units must be allowed for in the thermal and structural design of the blanket.

A regular pattern of blanket units will make for ease of handling. In addition the overall reactor design must take account of the needs of blanket handling in order to avoid unnecessary conflict with other reactor components.

RESULTANT CONSTRAINTS ON THE DESIGN OF OTHER REACTOR COMPONENTS

26. Space between blanket and shielding for manipulation of blanket components must be provided either as a permanent empty space or by the removal of other equipment which might occupy the space while the reactor is operating. This means for instance that the primary field windings, which may be required to initiate the plasma current in a Tokomak reactor, must either be demountable, if they occupy this otherwise free space, or they must be located within or behind the magnet-shield (Fig. 8). In either case the theoretical optimum layout with the windings evenly distributed around, and close to, the outside of the blanket cannot be achieved.

27. The blanket coolant ducts are a potential impediment to blanket removal in modules, but can be suitably disposed. Subsidiary pipes and cables for instrumentation, sampling, etc., should be similarly arranged.

28. In order to conform with the concept of a demountable blanket the magnet-shield would be a semi-continuous construction with appropriate apertures for access by the blanket-handling machinery. It must however also be possible to dismantle sections of the shield to allow for magnet removal, and the magnet and magnet-shield foundations must allow adequate room for access by blanket-handling machinery underneath the shielding.

DEVELOPMENT OF A WORKING FUSION REACTOR

29. In operational terms a fusion-reactor blanket is analogous to the fuel elements of a fission reactor, and experience has shown the advantages of

being able to change the design of fuel elements in the light of development. Correspondingly it will be desirable to allow for improvements in the design of fusion-reactor blankets by replacement of blanket components by new ones of improved design. A regular design of blanket with easily removable sections would satisfy these requirements.

30. The transition from large plasma-physics experiments to a working fusion reactor will pose severe engineering problems arising from the peak levels and gradients of neutron flux and thermal flux in the system. The fact that the first fusion reactor will be designed before much information is available on these matters will require a high degree of flexibility in its design. This reactor will be its own test bed, and only in a fully demountable system will it be possible to make the necessary changes in design to permit sufficiently rapid development of a commercial reactor.

DESIGNING FOR AN ACCEPTABLE LOAD FACTOR IN A POWER REACTOR

31. An acceptable performance in a power reactor is a load factor of at least 75%, coupled with a pattern of operation which avoids protracted periods out of service but which may include weekend shutdowns with a duration of up to 60 hours. If fusion reactors are to be integrated into power-generation systems without excessive duplicate or standby plant their operating capability must conform to this pattern. We must therefore develop techniques for renewing sections of the blanket structure within an overall shutdown period of little more than two days. In order to do this the operations must be kept down to a level at which they can be executed rapidly.

DISCUSSION

32. We are not at present in the position of designing a fusion reactor because the physics of such a machine has yet to be demonstrated. It is nevertheless apparent that to develop the technology of fusion reactors is a major task. How we organise our resources in the execution of this task will depend upon our understanding of the objectives to be achieved, and in order to define these objectives we must formulate design principles for a fusion reactor. In this way the major areas of development can be made clear and resources deployed accordingly.

33. A consideration of blanket-structure renewal illustrates the point. Major areas of design and development are revealed, and the inter-relationship

of the separate parts of a fusion reactor within the overall design is apparent. I have indicated some features of the structural design of the blanket. There is clearly a large area for development in producing a suitable liquid-metal-tight joint for the lithium supply to the blanket. The location of primary field windings relative to the blanket is an example of inter-relationships.

CONCLUSIONS

34. The life of a fusion-reactor blanket structure cannot be accurately predicted and random failure of blanket components at any time in the life of the reactor cannot be entirely ruled out. Flexible designs with interchangeable parts would be advantageous in prototype reactors.

35. It must therefore be arranged that blanket components can be renewed, and in units that can be conveniently handled, so that the reactors can achieve satisfactory operating load factors.

REFERENCES

1. Mitchell, J.T.D. and George, M.W. A Design Concept for a Fusion-Reactor Blanket and Magnet-Shield Structure. CLM-R121 1971.

2. File, J. et al. Large Superconducting Magnet Designs for Fusion Reactors. I.E.E. Applied Superconductivity Conf. 1972.

3. Mitchell, J.T.D. and Hancox, R. A Lithium-Cooled Toroidal Fusion Reactor. Inter Society Energy Conversion Engineering Conference, San Diego, U.S.A. 1972.

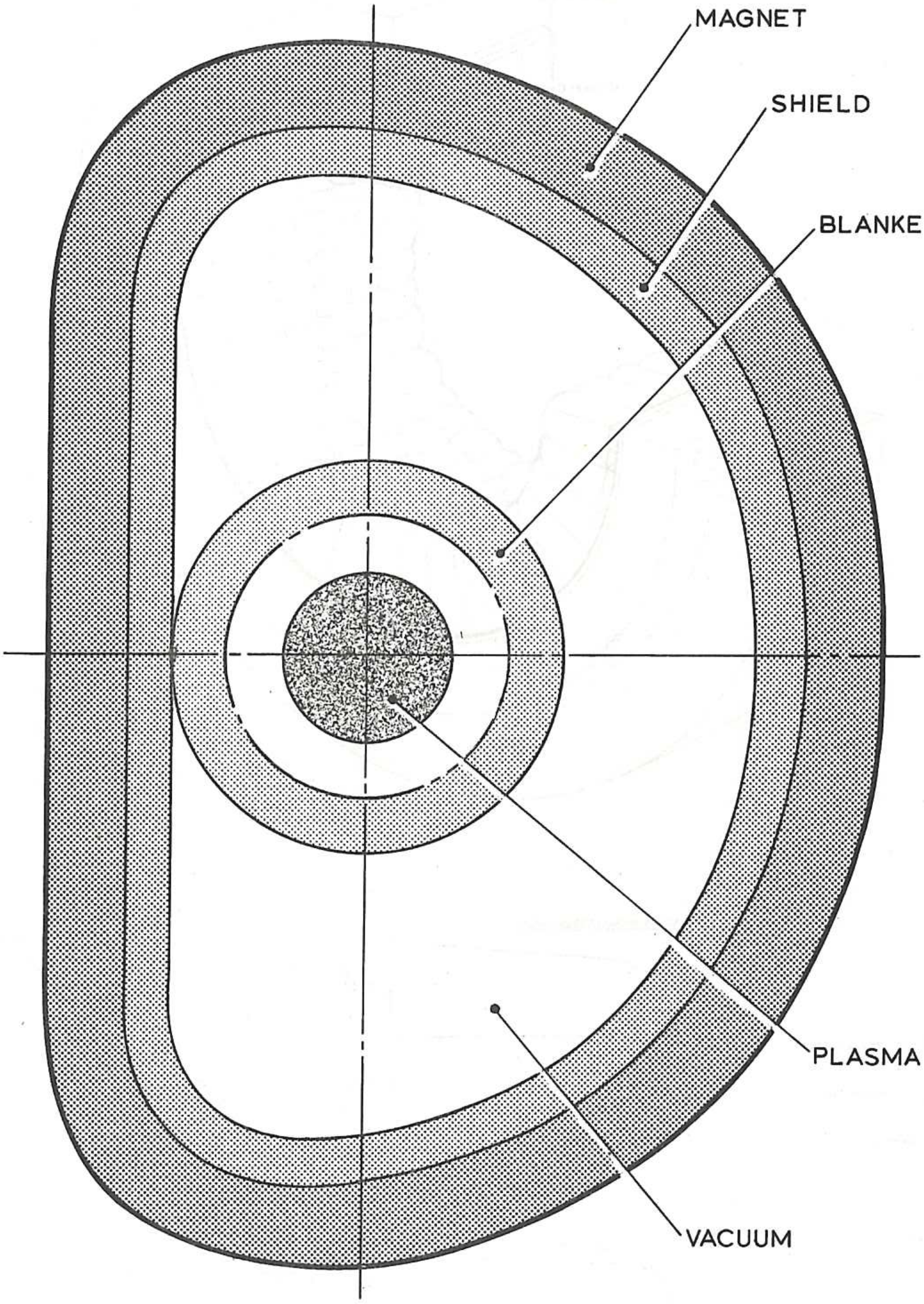

Fig.1 Spacious "D"-shaped magnet cross-section CLM-P351

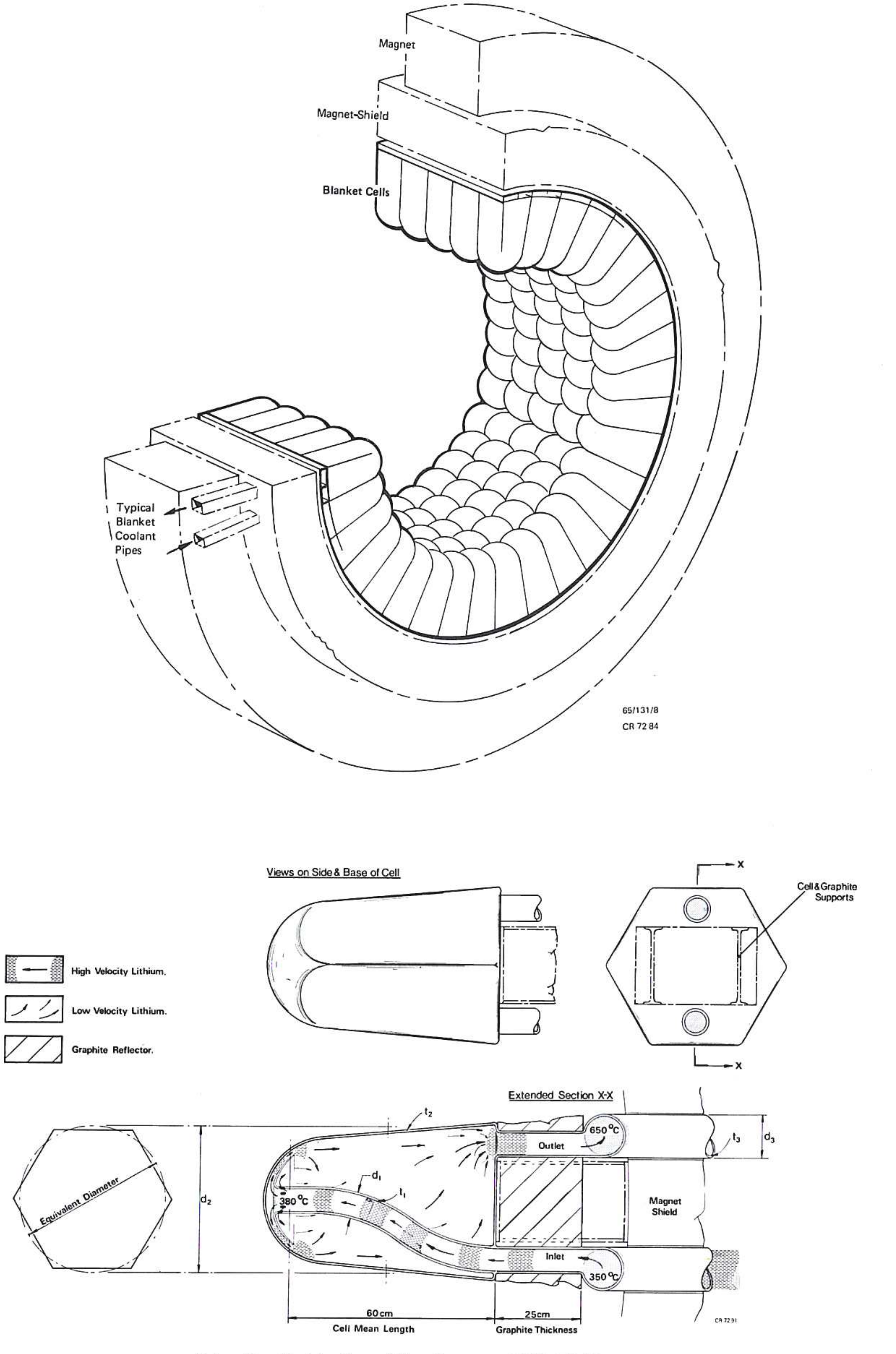

Fig.2 Cellular blanket CLM-P351

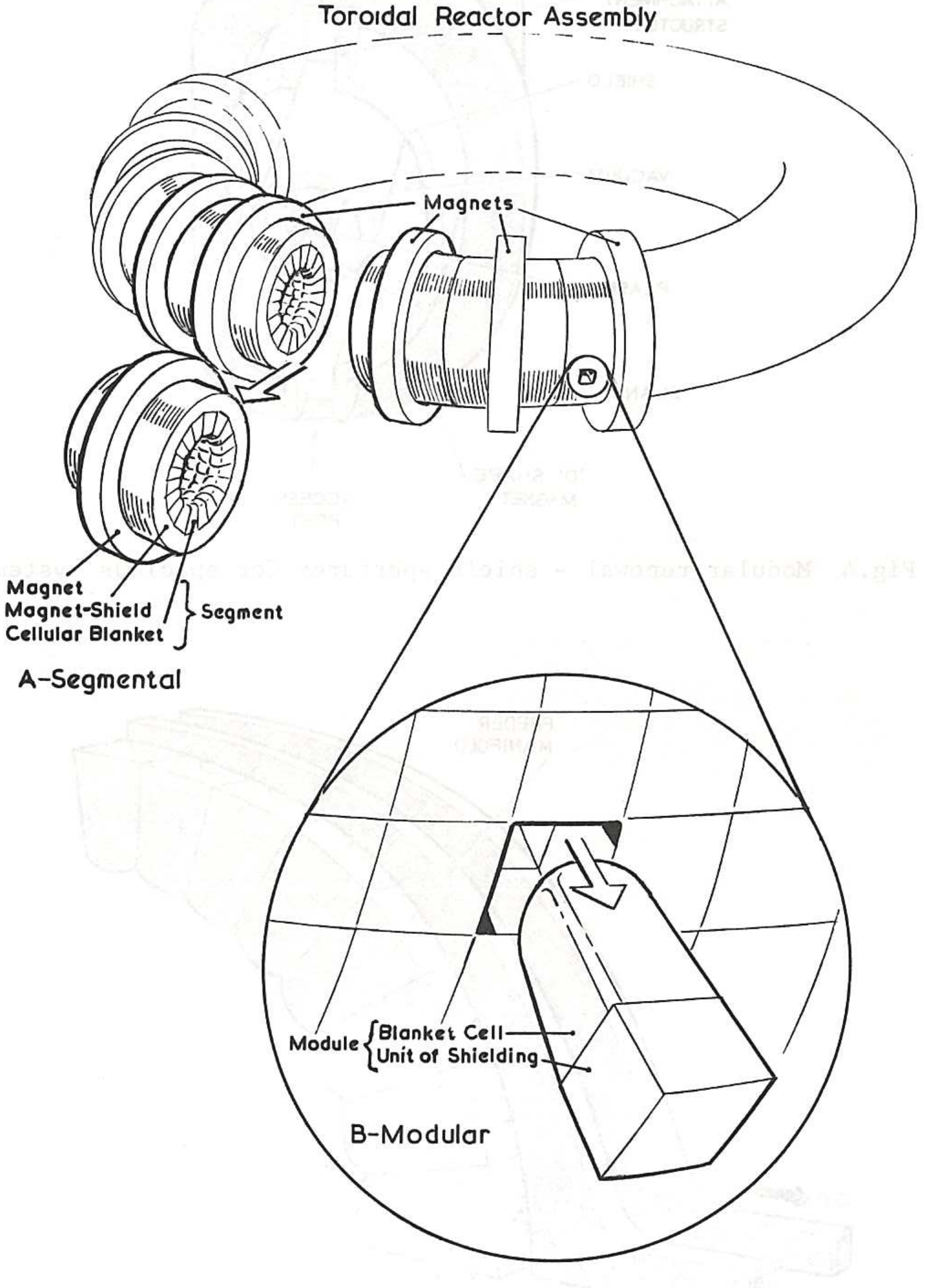

Fig.3 Modular and segmental renewal CLM-P351

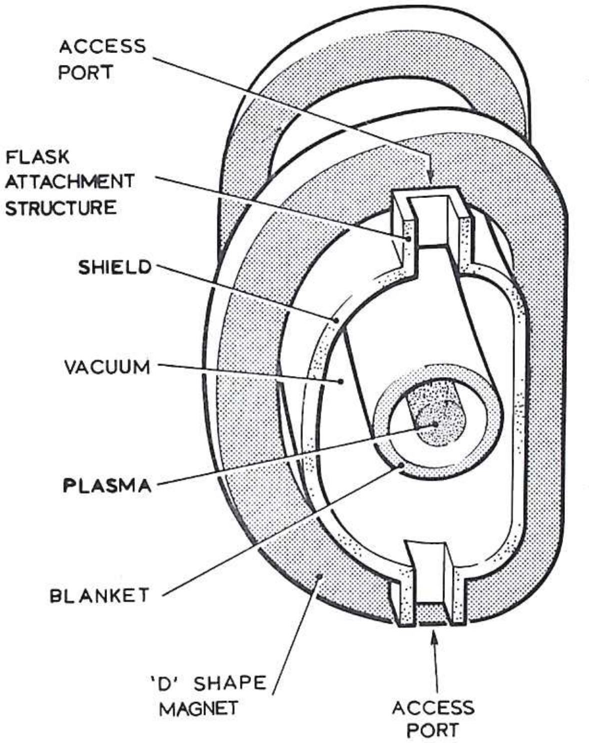

Fig.4 Modular renewal - shield apertures for spacious system

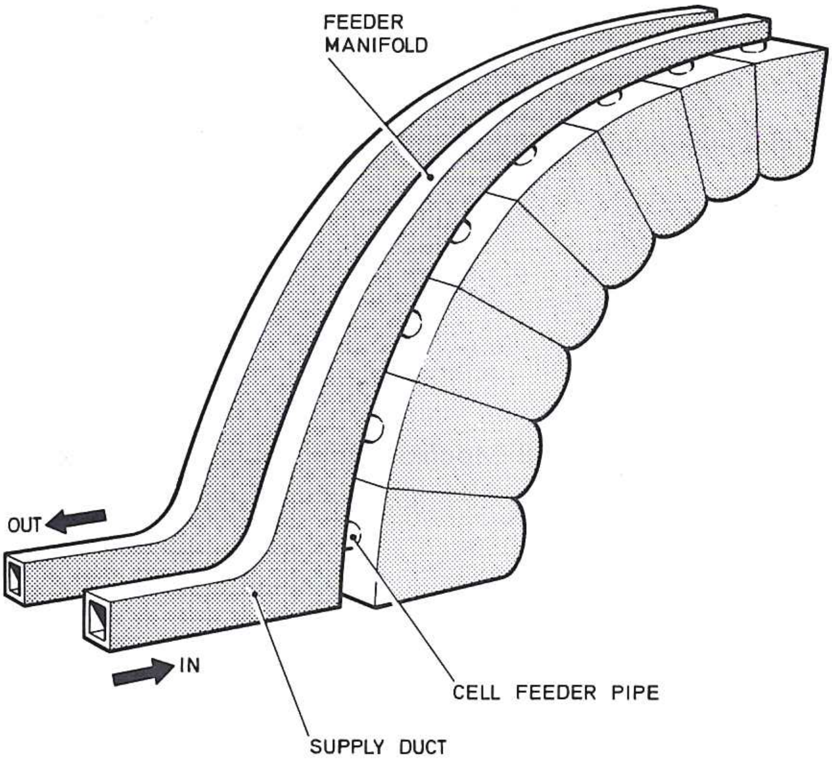

Fig.5 Lithium supply lines to module and manifolding

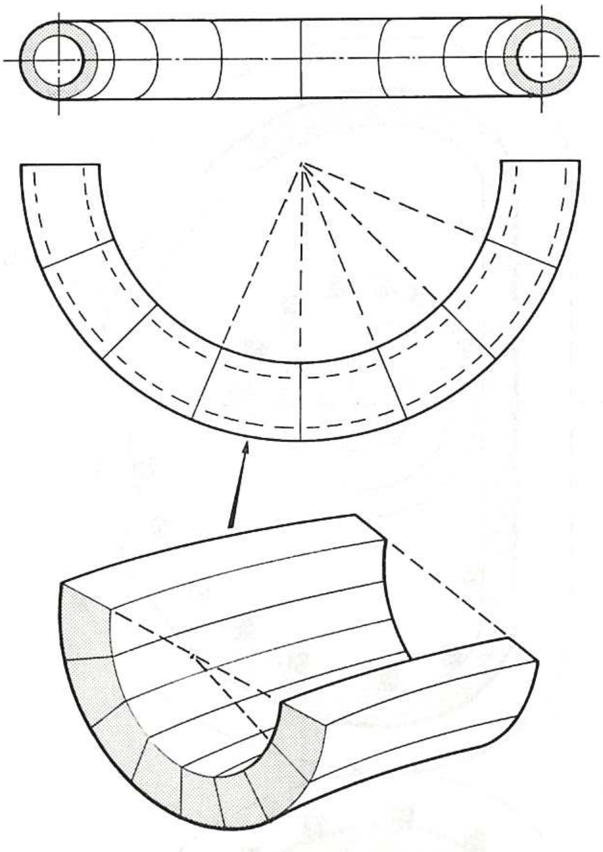

Fig.6 Cell geometry CLM-P351

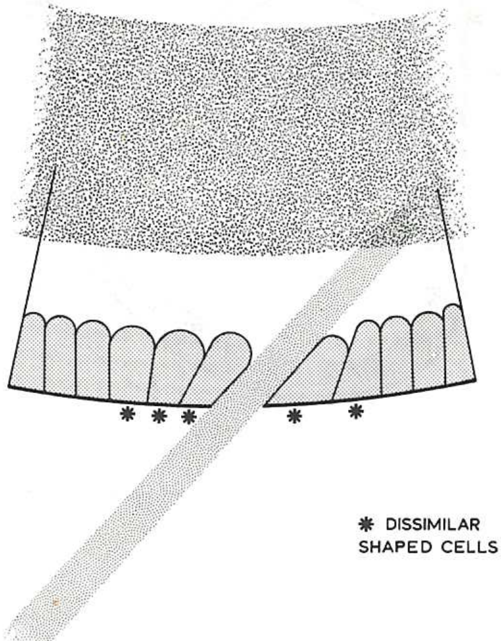

Fig.7 Blanket aperture CLM-P351

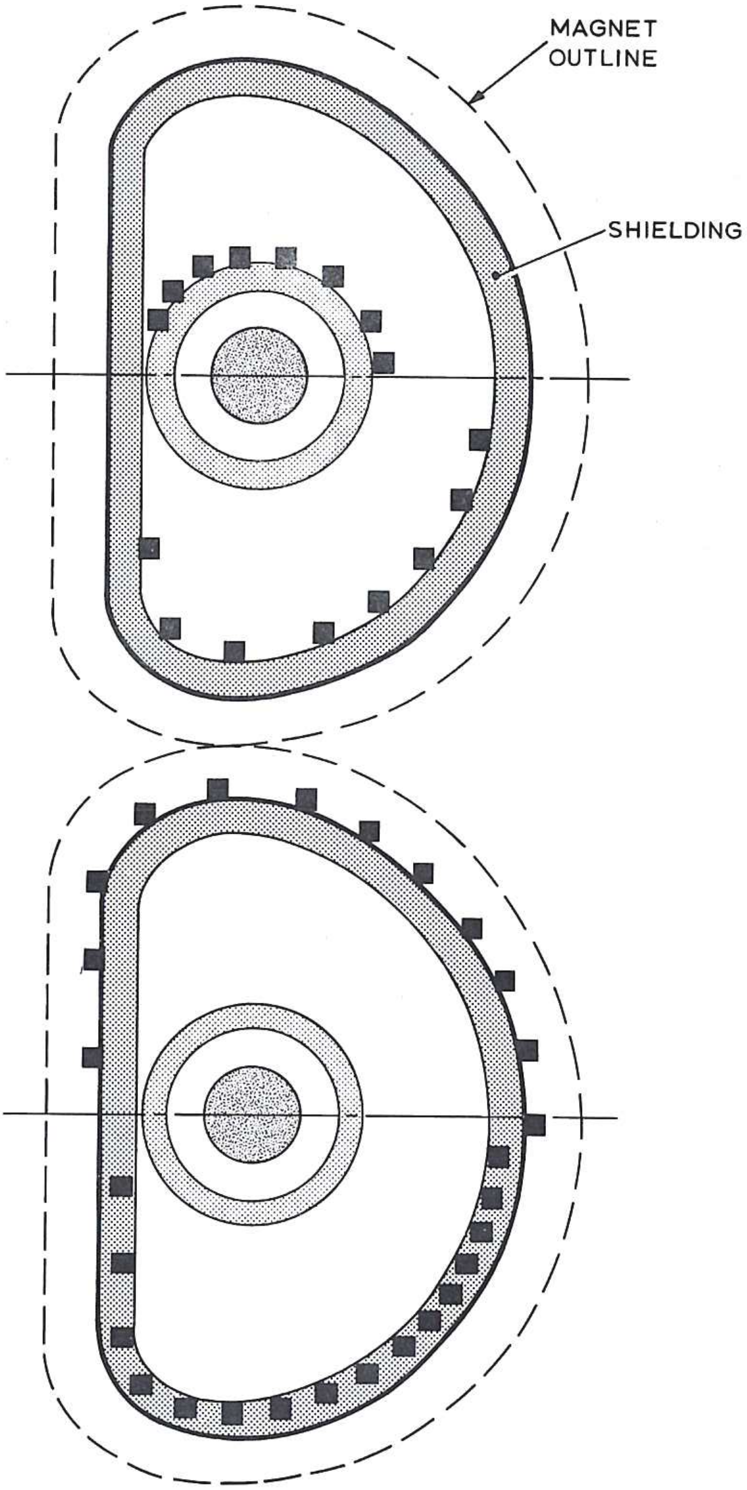

Fig.8 Location of primary field windings