THE ADVANCED NEUTRON SOURCE DESIGN - A STATUS REPORT*

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Abstract

The Advanced Neutron Source (ANS) facility is being designed as a user laboratory for all types of neutron-based research, centered around a nuclear fission reactor (D_2O cooled, moderated, and reflected), operating at approximately 300 MW_{th}. Safety, and especially passive safety features, have been emphasized throughout the design process.

The design also provides experimental facilities for neutron scattering and nuclear and fundamental physics research, transuranic and other isotope production, radiation effects research, and materials analysis.

Design Basis

The basic reactor design concept is derived from the technical objectives (Table 1) and the project's philosophy of minimizing technical risks and safety issues by relying only on known technology to meet the minimum design criteria.

The main scientific justification for the project, expressed by the National Academy Committee on major materials facilities[1] is the U.S. need for a world-class neutron scattering facility. The essential requirements are for a very high flux of thermal neutrons in a region that is accessible to beam tubes and with space for one or more cryogenic moderators large enough to remoderate the thermal neutrons to much lower energies, producing so-called cold neutrons.

Design Concept

It is clear, to meet those requirements that the reactor must produce a large number of fission neutrons, i.e., it must have enough power. In addition, the requirements dictate certain other design features (Table 2) which are very different from power reactors and have implications (many of them positive) for the safety analysis of the reactor (Table 3).

The annular, involute geometry of the fuel plates is copied from the High Flux Isotope Reactor (HFIR) and the reactor at the Institut Laue-Langevin (ILL) at Grenoble. The aluminum clad mixture of U_3Si_2 fuel particles and aluminum powder has been developed and extensively tested

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by the Reduced Enrichment Research and Test Reactors (RERTR) program although more tests at higher temperatures and burnup rates are underway or planned by the ANS Project. The short heated length of the HFIR core design and the long neutronic length of the ILL core have been combined (Fig. 1). Nominal specifications of the reference conceptual design are given in Figure 2 and in Table 4, which also includes the major thermal-hydraulic parameters of the core assembly.

The core cooling system design concept, which evolved through iteration among the design, safety, and R&D groups, incorporates many passive safety features (Fig. 3), as does the reactor system coolant components (Fig. 4).

Core Pressure Boundary Tube

The primary coolant pressure boundary in the region of the core is called the Core Pressure Boundary Tube (CPBT). It fits fairly closely around the upper fuel element (Fig. 5), and is made from aluminum 6061, for which ASME Section 3 Code Approval is being sought. Aluminum 6061 is chosen because of its high thermal conductivity and relatively low neutron absorption, and because there is extensive experience with it as a structural material in U.S. research reactors (for example, in the HFIR and the HFBR).

The fracture mechanics properties of aluminum 6061 are such that one cannot, as with steel, take any credit for leak-before-break detection nor, unless unacceptably thick sections are used, can one completely rule out flaw growth in components that are subject to tensile stress during operation. Thanks to the primary coolant circuit safety features illustrated in Figs. 3 and 4, we expect the core to survive without damage a large break in the CPBT downstream of the fuel elements, but not upstream. Therefore, a pressure vessel with an integral guard pipe concept has been adopted. In this design (Fig. 6), a continuous outer tube is the pressure boundary in normal operation. An inner guard tube is separated from it by a narrow, annular cooling channel. Holes or slots at the bottom of the lower guard tube would restrict the coolant loss rate to an acceptable value following failure of the outer tube. The flow rate in the cooling annulus is limited by a restrictor placed at the end of the upper fuel element: the flow rate must (7 m/s alongside the upper element sideplate, 4.2 m/s elsewhere) be high enough to cool the tubes, but low enough to provide a Bernoulli pressure rise that keeps the lower guard tube in compression (i.e., with no tendency for flaw growth) during normal operation.

Reactivity Control

The reactivity control system includes three hafnium rods in the central hole region, driven together from below by a mechanical system based on the successful HFIR design. These three rods can also be scrammed, with high acceleration, by individual springs that are individually released by magnetically held, fail safe mechanical latches, a design also based on the HFIR (Fig. 7). This system alone is capable of meeting the reactor shutdown criteria even if one rod fails to scram, and of shutting down the reactor (although by a smaller margin) even if two rods fail.

A second independent and diverse shutdown system is provided by eight rods in the reflector tank outside the CPBT. This set of rods is driven from above (so that, for example, a single missile will not damage both drive units). These outer rods are reset and latched hydraulically, and driven in for a scram by a combination of hydraulic and spring forces (Fig. 8).

In addition, burnable poison (boron) in the core controls the excess reactivity in fresh cores, reducing the negative reactivity that must be provided by the moveable control rods.

Table 5 outlines the reactivity balance of the core and other major contributors.

Reactor Internals

Among the components inside the core pressure boundary tube are the core support structure; the inner control rod guides, supports, linkages, stops, position switch actuators and drive springs; the flow screens at the entrance to the fuel elements; the irradiation facilities for materials testing and transuranium production; the instrument lead assemblies for the materials testing capsules; and the central hole flow restrictor.

Reflector Tank Internals

There are major items of equipment in the reflector tank which can influence the core reactivity and the thermal neutron flux. Table 6 is a preliminary listing of items included in the conceptual design.

Building Design

The overall budget design (Fig. 9) is also an important contributor to the safety, security, and accessibility of the scientific and reactor facilities. It provides physical barriers, formed from the massive containment and shielding structures, between sensitive or higher risk areas on the one hand, and the laboratories, offices, and experimental space of the users on the other.

IN-CORE MATERIALS IRRADIATION FACILITIES

	Goals		
Parameter	Small specimens	Larger specimens	ANS
Capsule dia, mm	16	46	48
Capsule length,mm	500	500	500
Total no. of positions	10	10	10
No. of instrumented positions	8		5
Fast flux, 10^{19} $m^{-2}s^{-1}$	≥1.4	≥0.5	2.9
Fast/thermal ratio	≥0.5	≥0.3	1.1
Axial flux gradient over 200 mm, %	≤30		14
Damage ratio (dpa/y in stainless steel)	≥30	≥8	
Nuclear heating rate (w/g in stainless steel)	≤54	≤15	78(max)/72(av.)

Table 1. **Advanced Neutron Source Project technical objectives**

- To design and construct the world's highest flux research reactor for neutron scattering
    - -5 to 10 times the flux of the best existing facilities
- To provide isotope production facilities that are as good as, or better than, the High Flux Isotope Reactor (HFIR)
- To provide materials irradiation facilities that are as good as, or better than, the HFIR.

Table 2. Design features and scientific requirements

Feature	Relationship to Scientific Requirements
Heavy Water Coolant	Reduces (compared with light water) the moderation of fission neutrons within the fuelled region, thus increasing the number of neutrons thermalized outside the core where they are potentially available to the beam tubes.
Small core volume	Reduces the surface area through which the reflected, thermalized neutrons must pass, thereby increasing the flux. Also reduces the moderation of fission neutrons within the fuelled region.
Heavy Water Reflector Region	Low absorption of thermalized neutrons, thus increasing the number potentially available for extraction in beam tubes or guides. Provides a large volume of high thermal neutron flux in which the cold moderators can be accommodated outside the core. Can easily accommodate complex shapes of experimental equipment, and is not subject to radiation damage.
Low temperature reflector	Thermalize neutrons at lowest practical temperature coolant (for thermal neutron beams and as source of neutrons for the cryogenic moderators).
High power (for a research reactor, much lower than power reactors)	Produces a large number of fission neutrons for subsequent moderation to thermal energies.
Large containment building	Provides floor space for experimental stations on thermal and hot-neutron beam tubes.

Table 3. Some features of the ANS research reactor with significant safety implications compared with typical tower reactors

Feature	Comment
Low thermal power level	~ 300 MW compared with ~ 3000 MW means less stored and circulating energy
Low fission product inventory at end of cycle (smaller core contains much less fuel)	~ 6 kg compared with ~ 100 kg means much lower source term
Small core	~ 100 kg total mass compared with ~ 100,000 kg means less chemical energy available for release
Lower core and reflector coolant temperature	<100°C compared with ~ 325°C, so that coolant water would not flash into steam during a pressure loss
Lower primary coolant pressure	~ 3 MPa compared with ~ 15 MPa means much less stored energy
High degree of containment	Containment bigger than a typical power reactor, to provide space for neutron beam experiments, but 10 times lower power level
Heavy water moderator	Longer neutron lifetime means slower reactivity transients
High power density (from high power and small core)	~ 5 MW/Litre compared with ~ 5 kW/Litre means more rapid heat up and dryout possible.
Occupied containment	Thermal neutron beam experiments must be located and operated at positions close to the reactor
High coolant velocity	High coolant velocity to accommodate high power density leads to very large flow forces on fuel plates and reactor internals
Short core life	The high power density leads to a short core life, with more frequent opportunities for refueling accidents.

Table 4. ANS reactor core nominal specifications

Quantity & Unit/Item	Reference Value/Material
Heat deposited in fuel, MW	303
Fission power, EOC, MW(f)	330
Core life, d	17
Core active volume, L	67.6
Core dimensions	See figure 2
Fuel form	U_3Si_2
Fuel enrichment, %	93
Fuel matrix	Al
Vol. % of fuel in fuel meat	11.2
No. of plates in upper element	432
No. of plates in lower element	252
Mass of ^{10}B, gm (BOC)	13
Fuel plate thickness, mm	1.27
Aluminum clad thickness, mm	0.254
Coolant channel gap, mm	1.27
Coolant	D_2O
Heated length, mm	507
Coolant velocity in core, m/s	25
Inlet pressure (in plenum), MPa	3.2
Core Inlet temp, °C	45
Annular gap in CPBT, mm	5
Coolant velocity in Annular gap, m/s	7
Equivalent break diameter of inner CPBT holes, mm	76 (lower) 51 (upper)

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Table 5. Conceptual reactivity balance

Potential Reactivity of the core at 20°C (BOC)	31,070 pcm
Temperature effect at full power	- 459 pcm
Core pressure boundary tube assembly	-5,150 pcm
Irradiation facilities	-2,000 pcm
Beam tubes	-3,820 pcm
Cold sources	- 470 pcm
Hot source	TBD
Other experimental facilities in reflector tank	-2,670 pcm
Central control rods (3)	-20,390 pcm[1]
Outer shutdown rods (8)	-15,330 pcm[2]

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[1] With outer rods fully withdrawn

[2] With inner rods fully withdrawn

Table 6. Reflector tank internals

Outer shutdown rod assembly

Hydraulic lines to outer shutdown rods

Tangential thermal beam tubes (7)

Thermal through beam tube

Slant thermal beam tube

Hydraulic rabbit tubes for light isotope production (3)

Hydraulic rabbit tube for transuranium production

Pneumatic rabbit tubes for analytical chemistry (5)

Isotope production vertical holes (4)

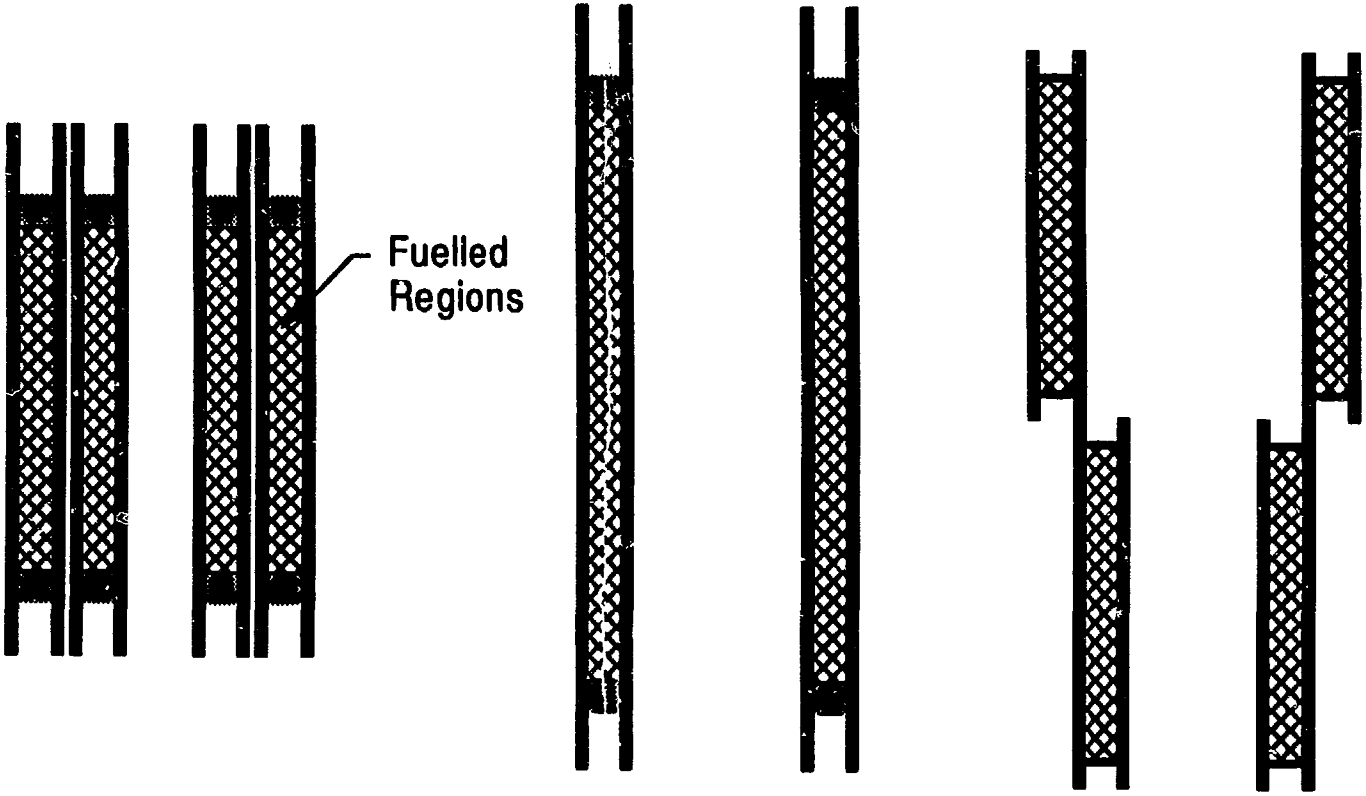
Slant irradiation tubes (2)

Cold source thimbles (2)

Hot source thimble

CPBT fasteners and seals

The ANS Reactor Core Design Combines The Best Features Of Earlier Designs



Fuelled Regions

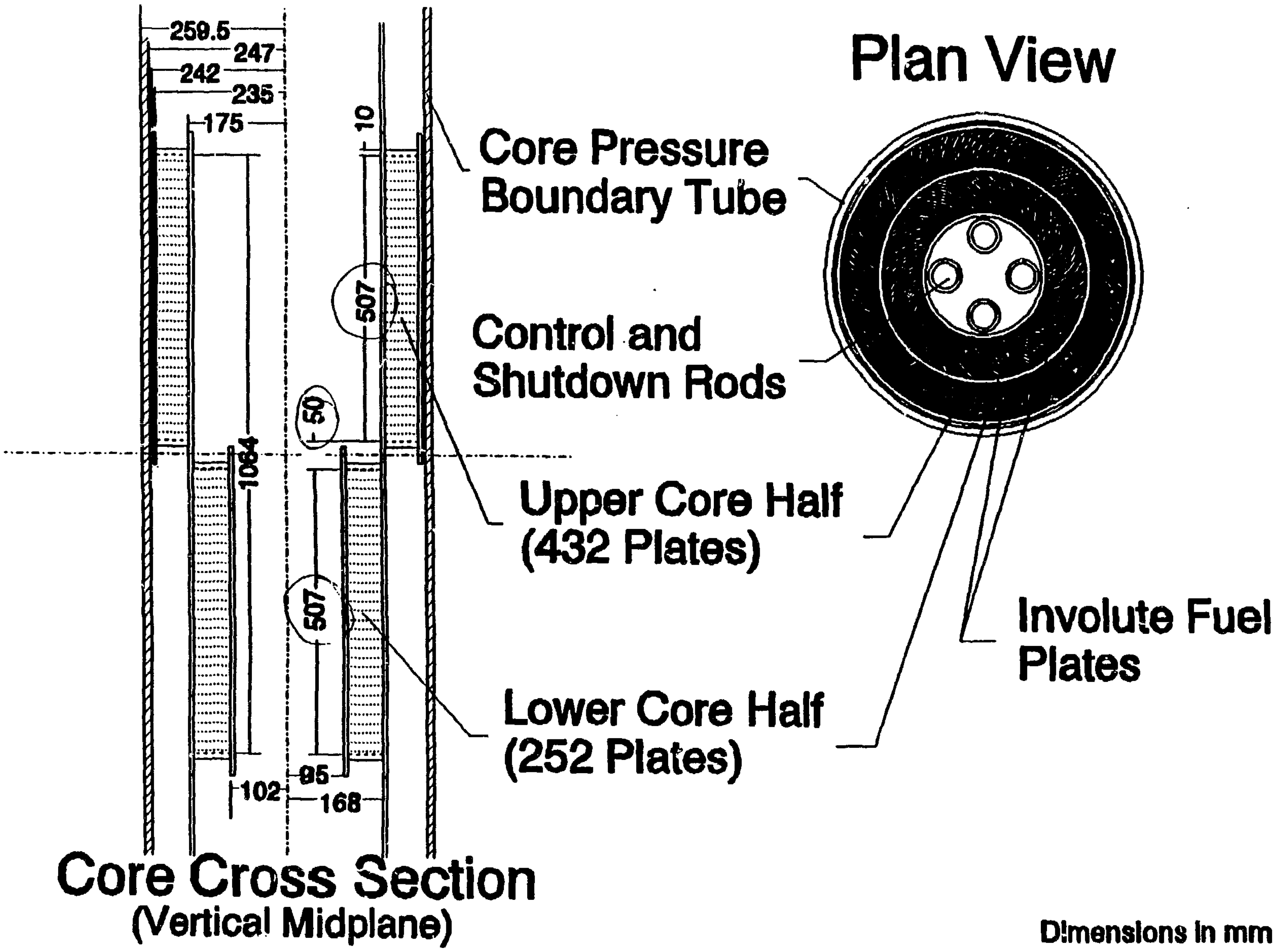
HFIR
Core
(Downflow)

ILL
Core
(Downflow)

ANS
Core
(Upflow)

Side by Side Comparison of ILL, HFIR, ANS Cores

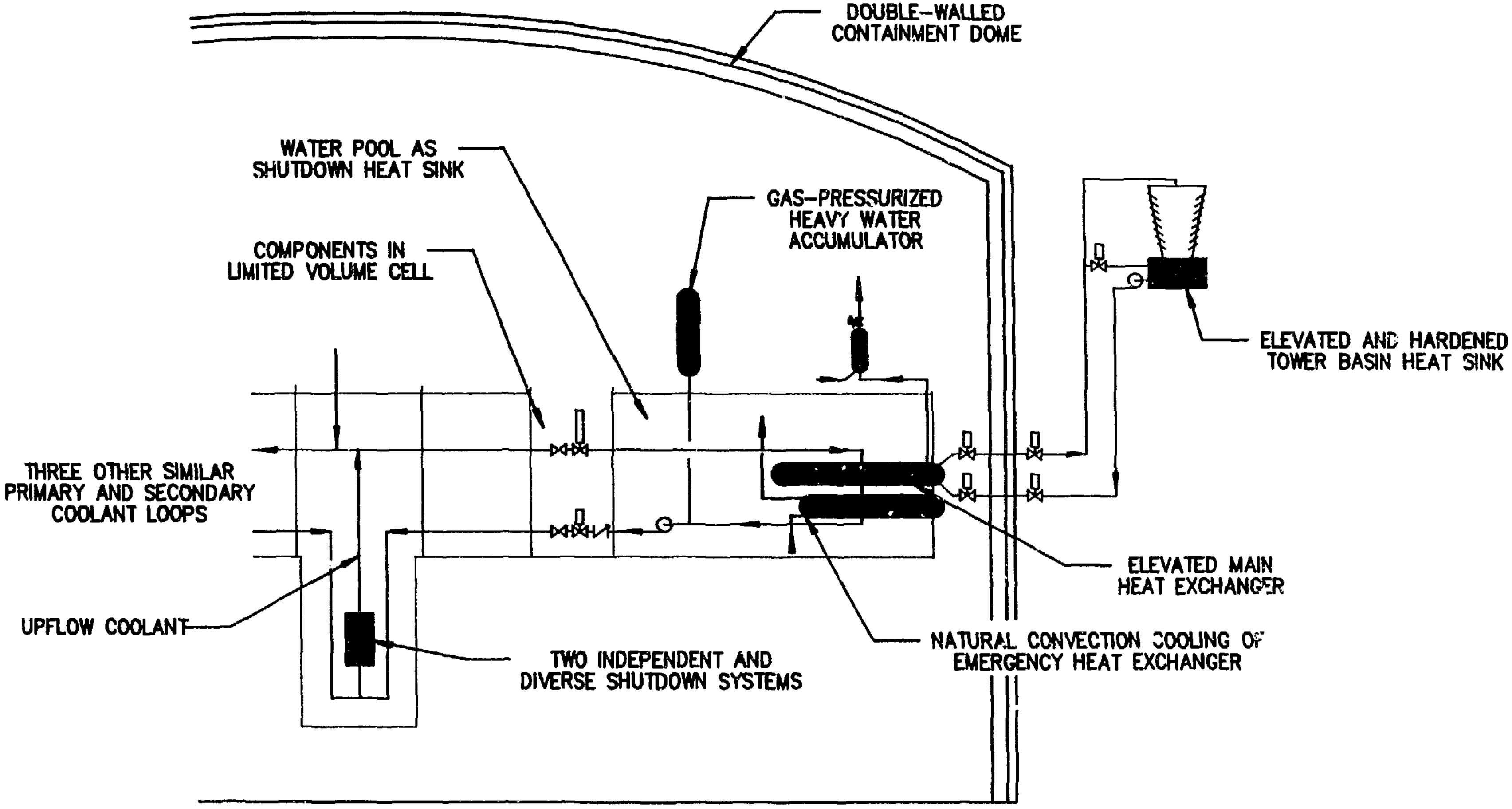
Fig. 1



Dimensioned Core Drawing

Fig. 2

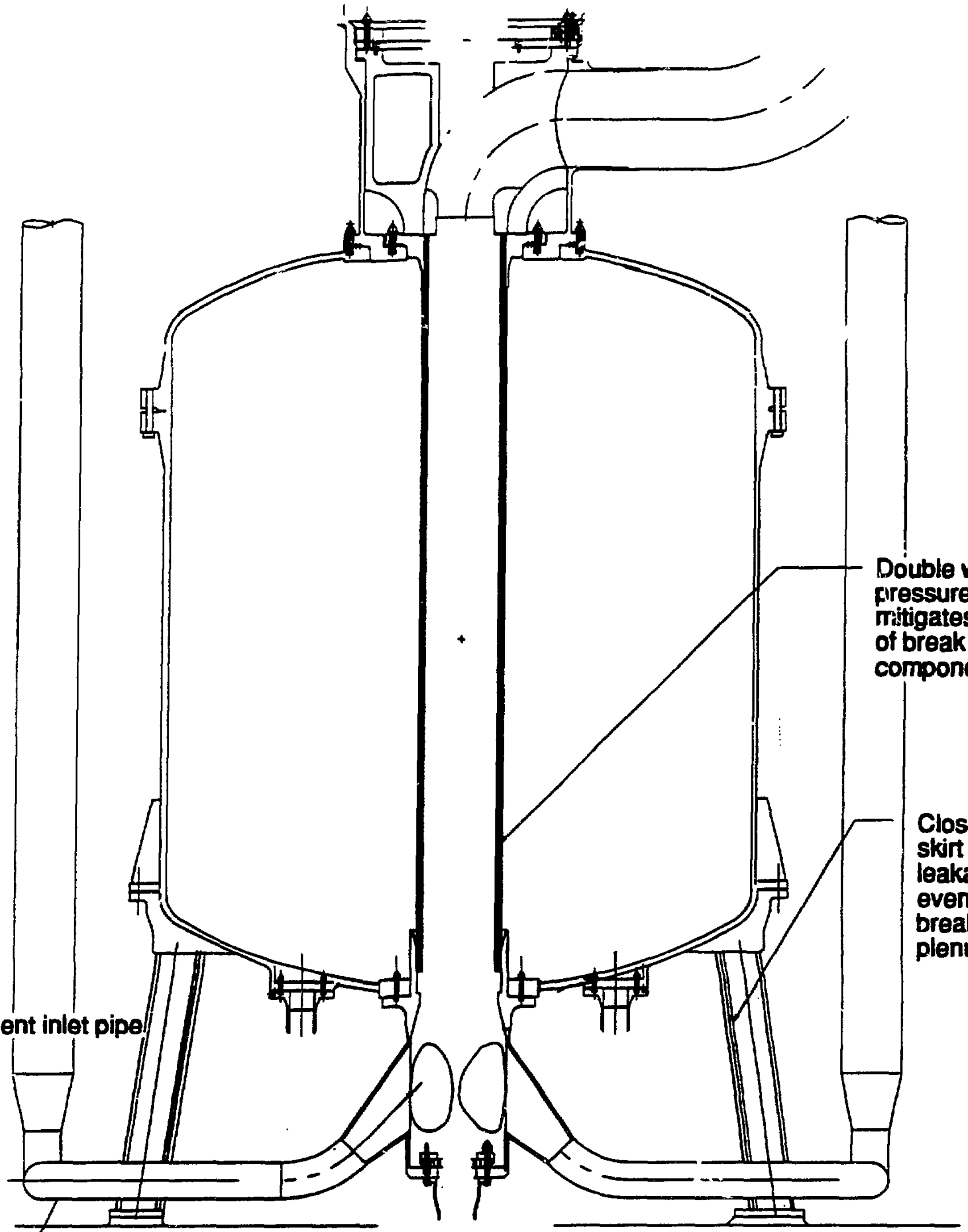
SOME SAFETY FEATURES OF THE ADVANCED NEUTRON SOURCE REACTOR DESIGN



Some Safety Features/Reactivity

Fig. 3

Fig. 4



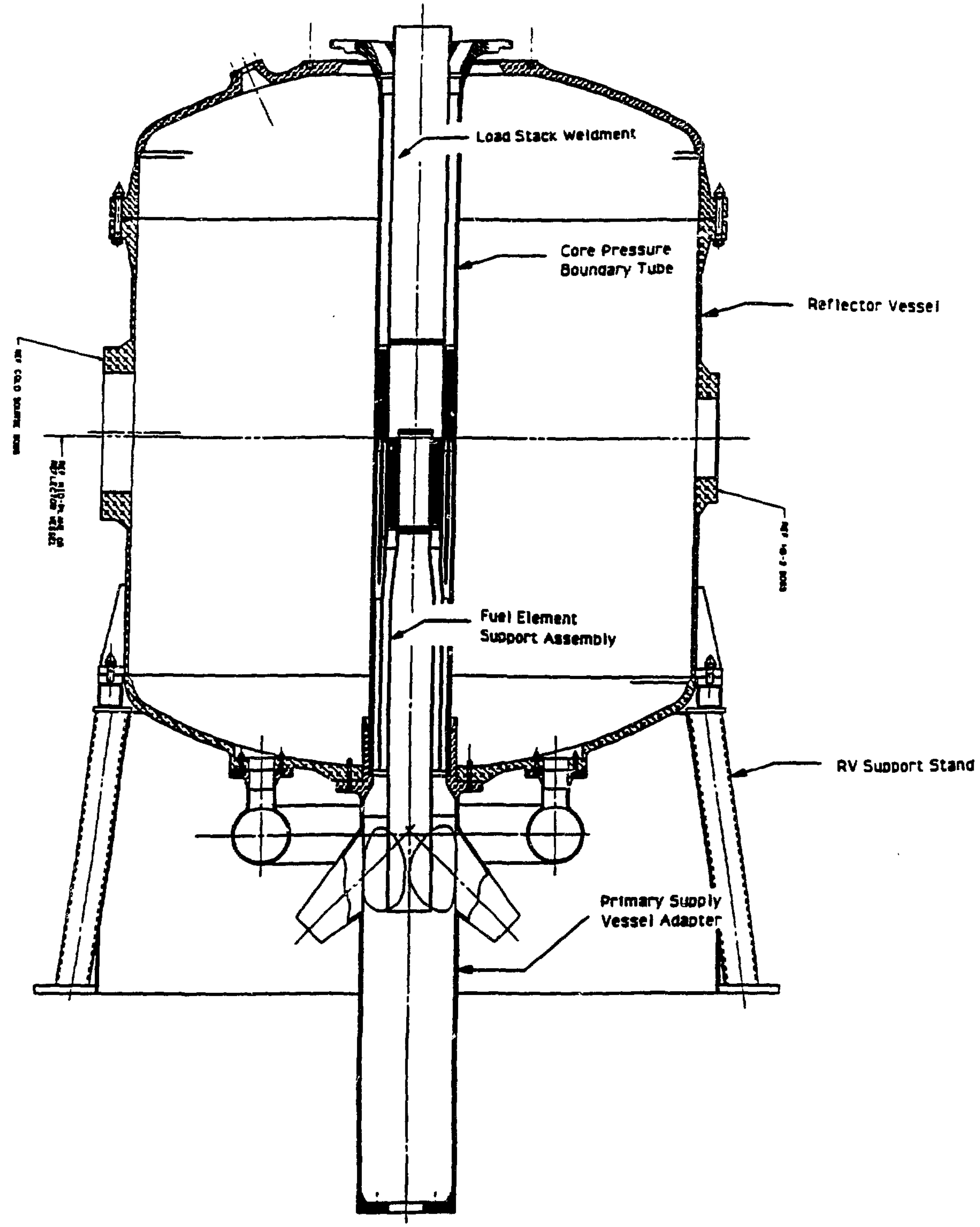
Double walled pressure tube mitigates the effect of break of this component

Close fitting skirt limits leakage in the event of a pipe break within the plenum

Convergent inlet pipe

Inertial flow diodes have a greater resistance to reverse than to forward flow, and also prevent rapid changes of flow speed in the event of large pipe break in the primary coolant system.

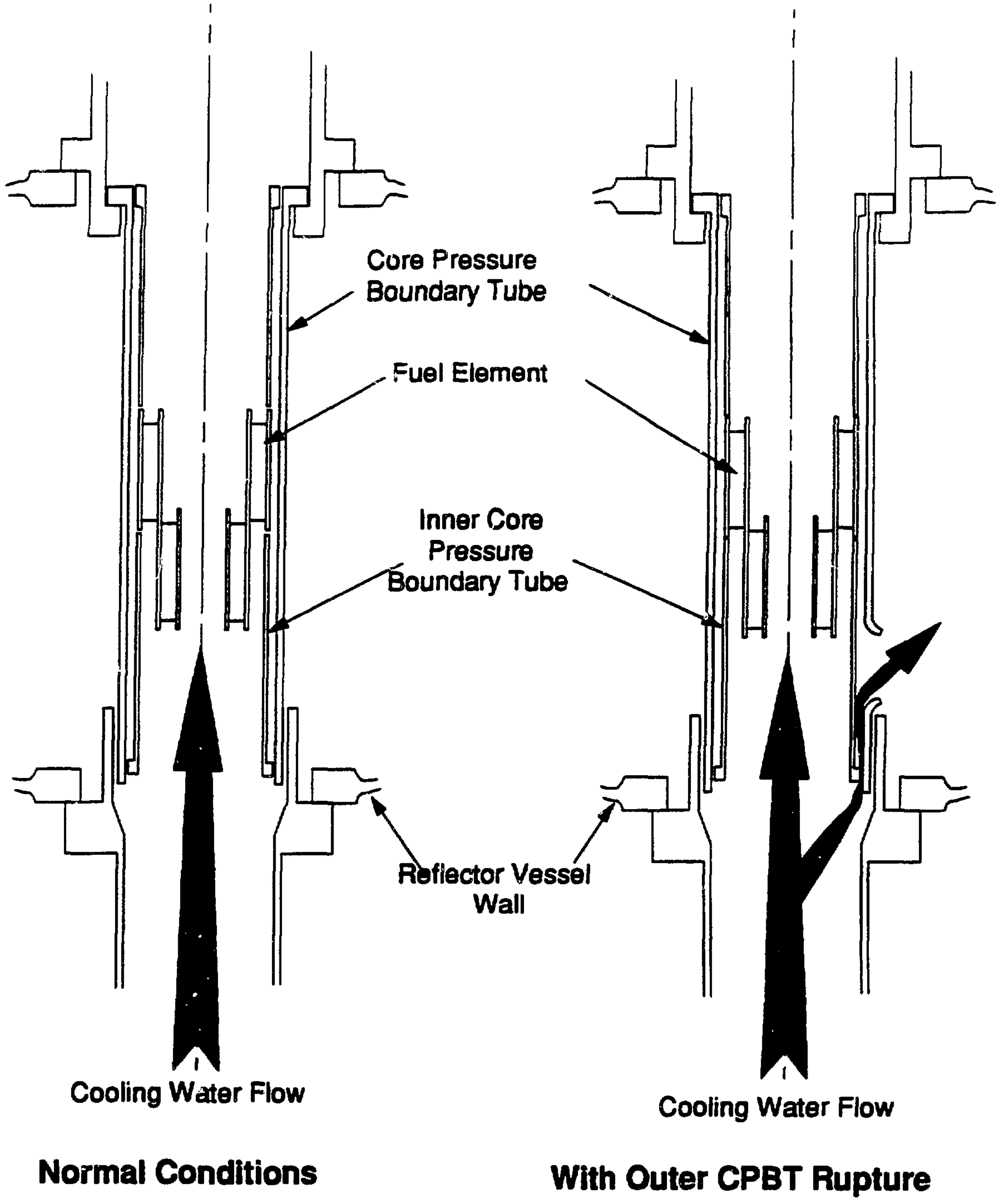
Some Safety Features of the Reactor System Coolant Components



Core Pressure Boundary Tube

Fig. 5

Principle of Double Wall CPBT



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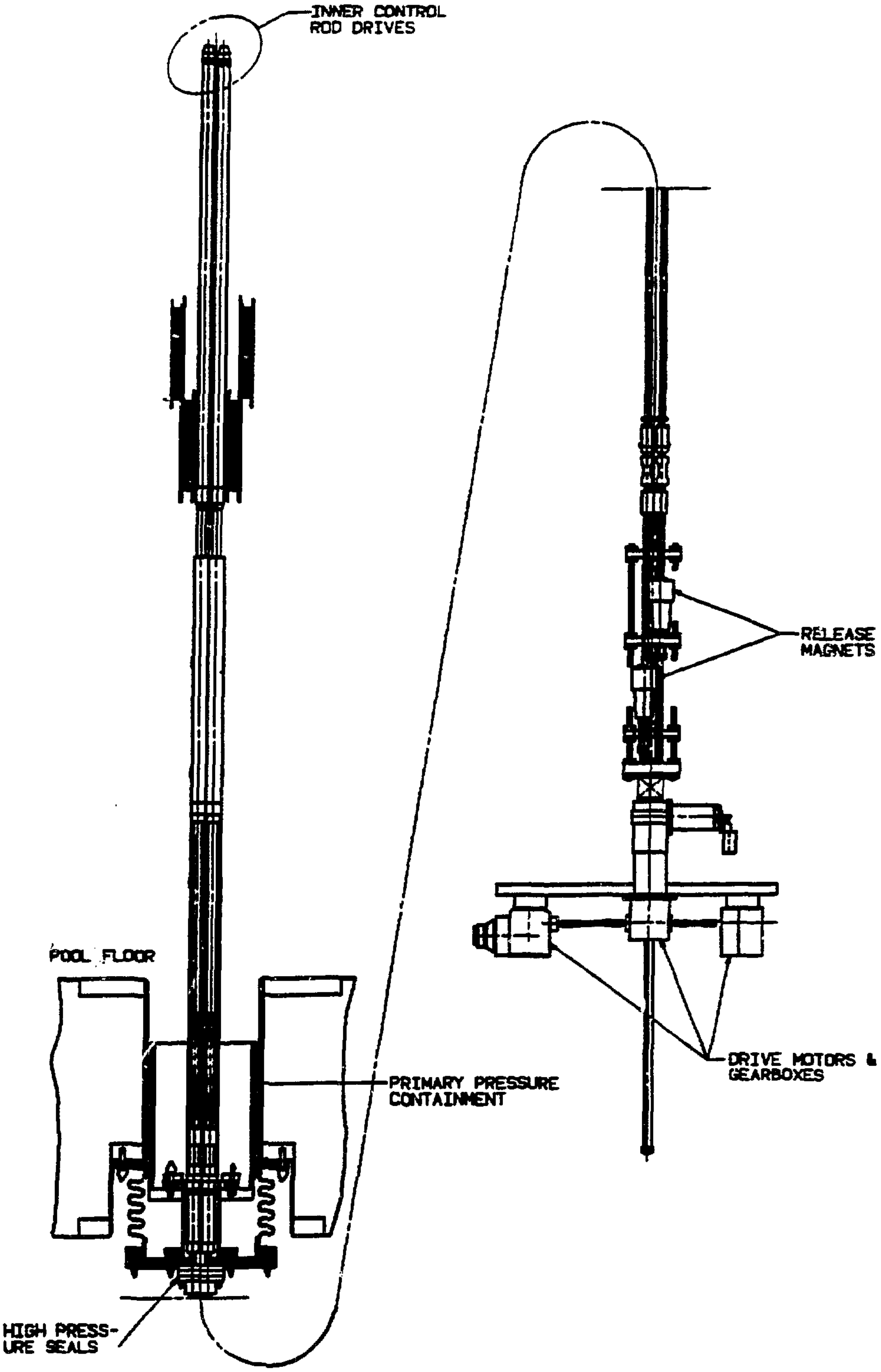
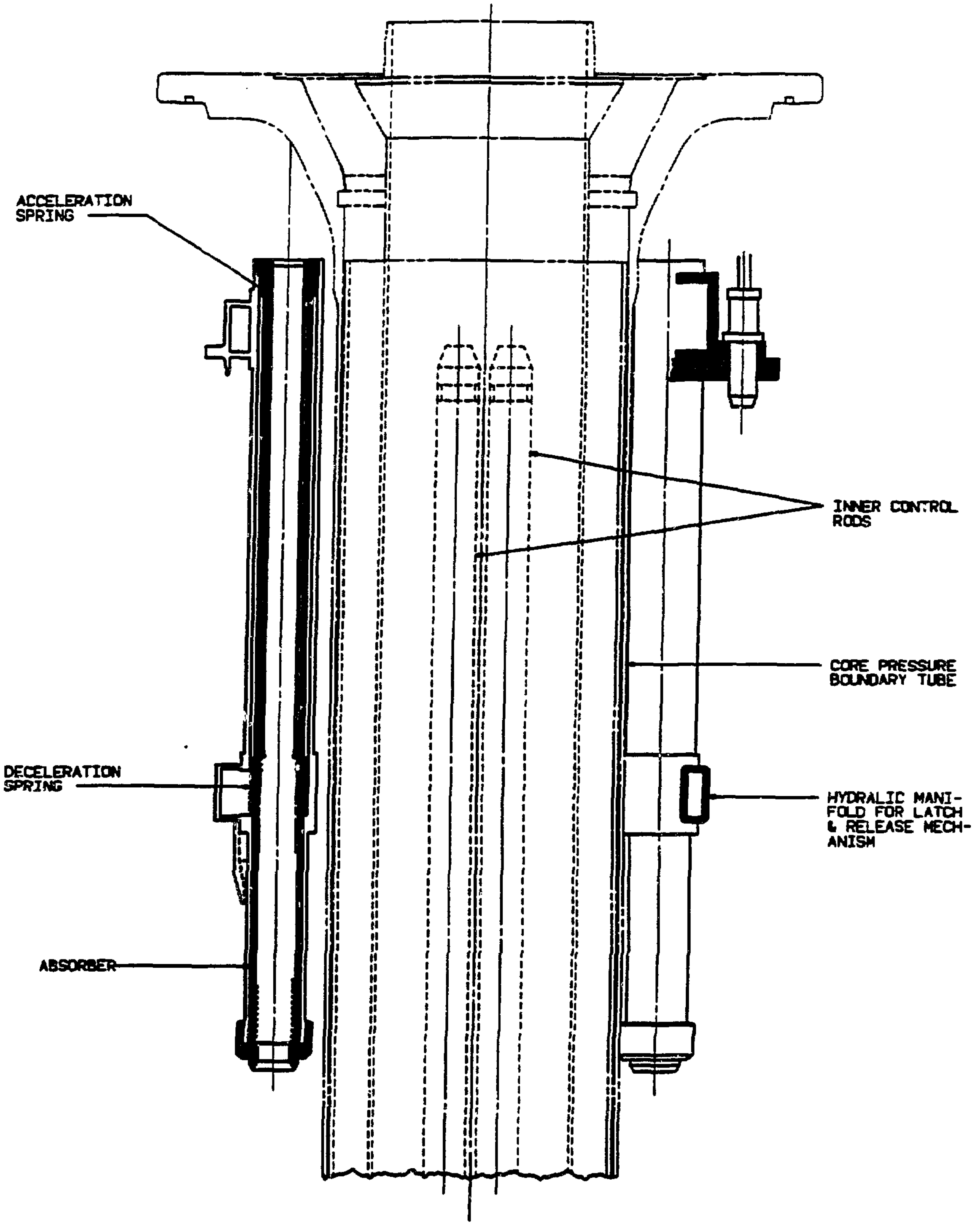
Principle of Double-Wall CPBT

Fig. 6



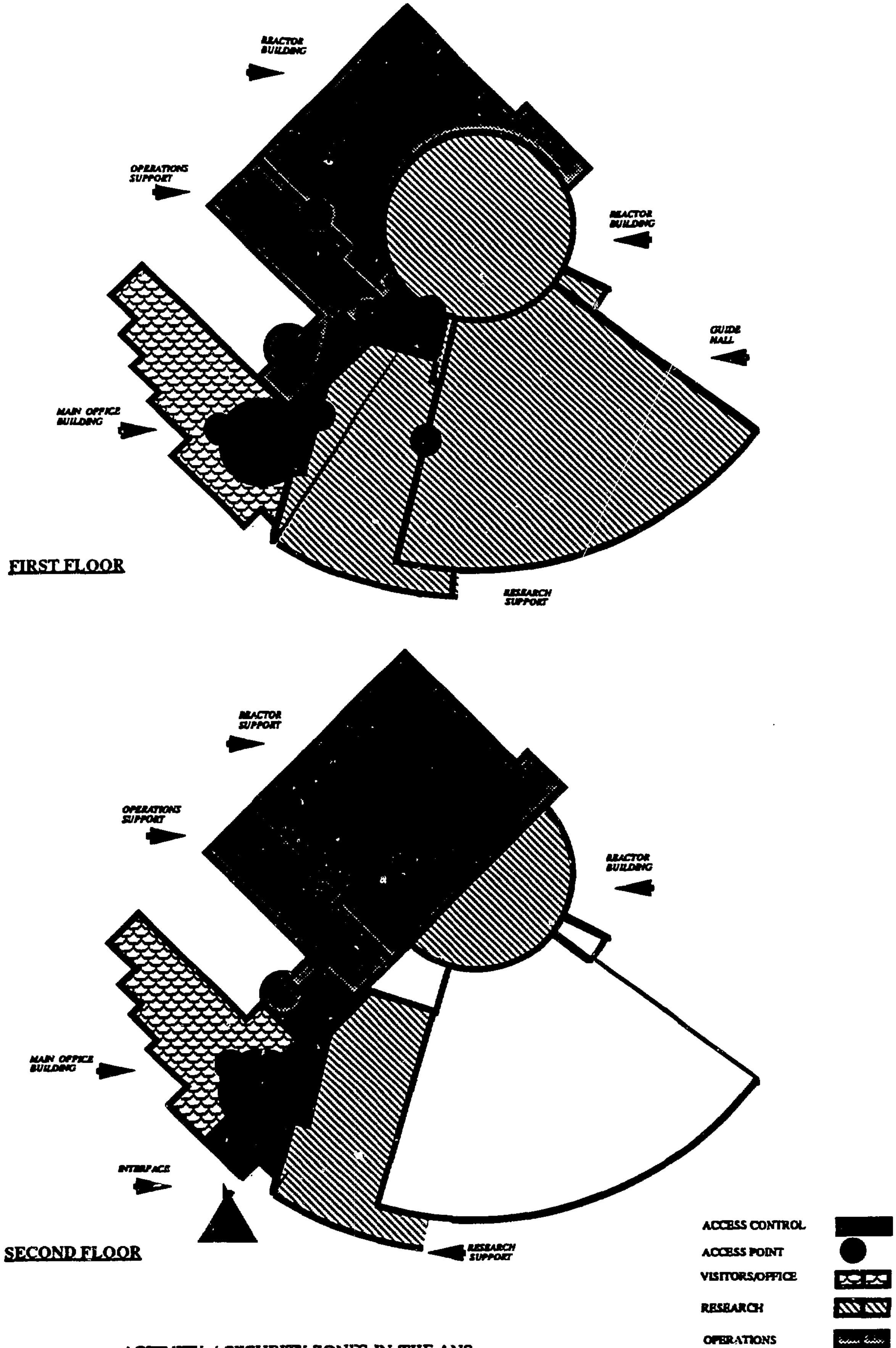
Inner Control Rod Drives

Fig. 7



Outer Shutdown System

Fig. 8



ACTIVITY / SECURITY ZONES IN THE ANS

Fig. 9 Building Design