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SETTLED BED FUEL REACTORS

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This paper* presents an outline of engineering design features of a group of nuclear reactors having in common the use of particulate fuel capable of being fluidized in liquid media.

Fluidization of particulate fuel in nuclear reactors offers major potential advantages in that it gains the quality of mobility in the otherwise rigid fuel thereby allowing long burnup periods and facilitating the transfer of fuel to, from, and within the reactor. In cases where relatively low thermal conductivity fluids such as water and organics are the fluidizing media, fluidization greatly enhances the heat transfer capabilities of the system. In the present group of reactor designs, however, the fluid associated with the particulate fuel is a liquid metal in all cases and, consequently high capacity for transfer of heat in the fuel systems is available regardless of whether the fuel is in the fluidized or the settled state. As a result, considerable latitude in the approach to the engineering design problems is gained.

Among the reactor designs considered two concepts, a sodium cooled thermal reactor, and a lithium (7) cooled thermal reactor call for the use of small particle size fuel (100 μ to 200 μ) which would be maintained as settled beds during normal operation of the reactor, but with the alternative that the beds be maintained in the fluidized state if further investigation should so indicate. The other two concepts are both sodium cooled fast breeder reactors utilizing larger size fuel (up to $\frac{1}{4}$-inch spheres) maintained only as settled beds

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during normal operation. With the smaller size fuel the coolant would flow in heat exchanger tubes within the bed, whereas with the coarser fuel the coolant would pass directly through the bed of fuel particles. All the designs call for fluidization of the beds during transfer of fuel from and to the reactor and of fuel distribution within it.

In general one would expect to find lower fuel cycle costs with the use of nonrigid fuel systems than is the case with the conventional solid fuels, as a result of lower fuel fabrication costs, higher burnups, and lower excess reactivity requirements. The question is whether these costs advantages would be offset by increased core complexity resulting in higher fixed charges and increased operating and maintenance costs due to the fuel cycle. For this reason designs were evolved with particular attention paid to reducing complexity of the core structure. It should also be noted that all but one of the designs permit fission product contamination of the primary coolant. Thus, for the present, the final choice of a design in this regard would be determined by assessing the magnitude of the coolant contamination problem as shown by in-pile experiments performed during research and development phases. However, coating of fuel particles to prevent the escape of fission products to the coolant is a promising possibility.

The settled bed concept, with the coolant flowing directly through the bed, would seem to avoid or minimize some of the outstanding problems of the directly cooled fluidized bed reactor, namely, fluctuations in fuel density as a result of turbulence in the coolant flow and attrition or breakage of fuel material as a result of impact between particles. The use of solid reactor fuels in particulate form either as settled or fluidized beds offers the following advantages:

a. Maintenance of uniform distribution of the fuel-containing solids and, therefore, of the fuel density, throughout the entire core.

b. Overall mobility in the fuel permitting the particle suspension to flow in tubes connecting the reactor core region with an outside vessel (for fuel makeup and reprocessing) in response to pressure adjustment in the fluidizing liquid stream. Provision for fuel makeup at frequent intervals is itself an important advantage since only small amounts of excess reactivity would then be required.

c. With the small particle size fuel the low thermal conductivity of ceramic fuel materials such as UO_2 is not a limiting factor because of the high particle surface to mass ratio. (In the designs where the larger fuel particles are used, thermal conductivity and consequent thermally induced internal stresses within the particles become very sensitive design considerations).

d. Elimination of excessive fabrication costs commonly associated with the manufacture of solid fuel elements under close tolerance requirements.

e. Excellent possibility of very high burnup in the fuel.

f. Ease of reprocessing of the fuel due to the ability to transfer the fluidized fuel in the same manner that a liquid is transferred.

g. Assurance of achieving uniform burnup in the fuel by virtue of its mobility.

h. Confinement of the fuel to the core of the reactor while retaining the other advantages of a liquid fuel.

i. Use of the particulate form of solid fuel without the need to recirculate the fuel through pumps, valves, etc., and without problems of erosion or attrition of fuel particles. Even with fluidization of the smaller size fuel almost quiescent conditions obtain with the laminar flow state.

An experimental program has been carried out at Brookhaven on the performance characteristics of particulate UO_2-NaK systems at room temperature. Studies on the wettability of 100 μ UO_2 particles by NaK have shown that the material is readily wetted after reduction with hydrogen to give near stoichiometric U-O ratios followed by thorough degassing. It was then found that fluidized beds of UO_2 particles in NaK could be established in the usual manner and that they showed the desired characteristic of mobility. X-ray pictures of a UO_2-NaK fluidized bed are shown in Fig. 1. Other features of laminar fluidized beds which are of primary importance in the present studies were demonstrated using beds of 100 μ and 200 μ glass beads in water, (See Figs. 2 and 3). These features include uniform suspension and settling out in a continuous system made up of interconnected narrow channels, ease of transfer in tubes from one vessel to another, and general stability of such suspensions. No experiments have yet been carried out at BNL to represent the case where fluidization and transfer of the larger (up to $\frac{1}{4}$ inch) fuel particles would be involved, but such systems have been studied in detail by others and no serious difficulties with respect to fuel transfer are anticipated, however, the larger particle beds in turbulent flow systems certainly would not operate as smoothly as the smaller particle beds in laminar flow systems.

Of much greater importance and concern here is the problem of compaction of settled beds to dependably stable levels. A bed of spheres of equal diameter will, under ideal closest packing, have a void volume of 25.95 percent of the total volume of the bed. Closest packing is, of course, never realized when the spheres are packed at random such as when they settle from a state of suspension or fluidization. The problem in this regard, therefore, is to determine to what extent settled beds, with or without subsequent compaction, may be considered stable for dependable reaction operation. Moreover, the question of fuel particle sintering or "stitching" is a most prominent one which will require early investigation. Obviously, there are a number of other serious problems to be faced in any attempts to determine the feasibility of utilizing settled bed fuels for nuclear reactors. However, the economic advantage to be gained through the successful development of settled bed fuel reactors, stemming from the reduced fuel cycle costs associated with the mobile solid fuel, would seem to warrant an aggressive effort in this direction.

UO_2-SODIUM-GRAPHITE THERMAL REACTOR

Under this concept the granular fuel, (100 μ UO_2 in sodium), occupies a single continuous region which fills the spaces between the moderator-heat exchanger elements. These elements are arranged in a hexagonal pattern with each element equidistant from its neighbor. Confinement of the fuel in a single continuous region offers the advantage that only one set of pipes is required to provide for transfer of fresh fuel to and discharge of spent fuel from the reactor, and only one pipe would be required for entry of fluidizing sodium. The reactor is cooled with sodium and moderated with graphite. The active core is a 10 ft. right cylinder, and has a power output of 850 MW(t). A special feature of the design is that the coolant is carried in channels formed within the double walled cladding which encases the hexagonal graphite moderator blocks. Use of the combined internal heat exchanger and moderator elements greatly facilitates replacement of internal parts.

With this internal heat exchanger type of reactor the question of degree of separation of the fuel from the coolant stands out as a major consideration. Since complete separation of coolant and fuel would require a more complex heat exchanger and manifold system, some small degree of communication between the fuel and coolant regions is tolerated under this arrangement in order to gain a major simplification in the mechanical design. With uncoated fuel particles some direct fission product contamination of the primary coolant would result but the contamination should be held at low levels as a result of (1) maintaining the fuel bed in the settled state during normal reactor operation with no flow of sodium through the bed, and possibly, (2) maintaining a stratified protective layer of BeO particles on top of the fuel bed. The BeO would be introduced along with the fluidized fuel and would find its way to the top of the bed by virtue of its lower density. The advantages gained through the simplification of the internal heat exchanger system with its once-through flow arrangement would seem to outweigh the disadvantages imposed by low level fission product contamination of the primary coolant.

Reactor Core

The reactor core consists of a lattice of 217 graphite moderator logs and coolant tube elements in a 10 ft. diameter x 10 ft. long settled fuel bed surrounded by a reflector of graphite at the sides and top and BeO at the bottom. The weight of the core is supported by a bottom grid structure resting on beam supports welded to the flat bottom of the reactor vessel. The moderator log and coolant tube elements are free to expand upwards against a spring loaded hold-down structure located in the nitrogen gas blanket above the cooling sodium level. Twenty-five control rods are provided in the undisturbed lattice for shim and dynamic control and scram. The mechanical design of the calandria permits the removal of singular elements of moderator log and coolant tubes and reflector graphite elements without disturbing companion elements. In addition, the lower support grid structure as well as all other internal supports and piping are removable for maintenance or repair as required.

The general arrangement of core and reflector is shown in Figs. 4, 5, and 6.

Each of the 217 graphite moderator log and coolant tube elements is a right regular hexagonal prism approximately 7.1" across graphite flats with 15.5 ft. overall length. At its lower end, each element has tapered pipe fitting with a companion tapered fitting in the mouth of the coolant channel and support pipe column in the upper support plate. The coolant tubes are formed by welding a continuous rolled corrugated plate of 25 mil-304 stainless steel to the graphite moderator can, also 304 stainless steel, as indicated in Fig. 5, Detail Y. The corrugations form a series of ten 0.350-inch o.d. half-tubes per face. These tubes extend from a built-in plenum at the bottom of each element along the full length of the element. Inlet cooling sodium from the main inlet plenum passes through the support column channels into the bottom plenum of each graphite moderator log and coolant tube element and up through the corrugation tubes into the cooling sodium outlet plenum above the upper reflector section. Each moderator and coolant tube element is free to expand upwards against a hold-down spring into a guided pin connection at its uppermost extremity.

Particulate Fuel Handling System

The fact that a fluidized bed fuel may be treated somewhat as a liquid, insofar as its flow characteristics are concerned, permits the charging and discharging of fuel to and from the reactor through an interconnecting piping system. The fuel handling system provides for the maintenance of the fuel in the fluidized state in the reactor and in the external reservoir as required. The fuel suspension is transferred from one region to the other by means of simple adjustments of pressure in the fluidizing liquid circuits. The system, shown in schematic form in the flow diagram, Fig. 7, contains two independent liquid circuits, one of which serves to fluidize the fuel in the two or more external reservoirs during the fuel charging and discharging operations. This type of fuel handling system is applicable to all the reactors described in this paper.

Loading the fuel into the reactor is accomplished as follows. The desired quantity of fuel is first charged to the fuel reservoir and then fluidized by means of sodium flow from pump no. 2. The transfer line valve is opened, and the valve on the outlet line from the fuel reservoir is adjusted to pressurize the fluidized fuel, thereby causing it to flow through the transfer line and into the fuel region of the reactor. In order to discharge fuel from the reactor, the transfer line valve is opened, and the sodium return line valve is closed while maintaining the fluidizing sodium flow. The static head of fuel in the reactor causes the fuel to transfer to the fuel reservoir. At this time, the fuel may be blended with enriched UO_2 and returned to the reactor, or discharged to the spent fuel receiver for shipment to the reprocessing plant.

TABLE OF REACTOR CHARACTERISTICS

Engineering Data

1. Reactor Vessel

Design pressure:	75 psig
Design temperature:	$1000^{o}F$
Vessel ID:	14 ft-3 in.

TABLE OF REACTOR CHARACTERISTICS (cont.)

Engineering Data (cont.)

1. Reactor Vessel (cont.)

Vessel height:	22 ft-6 in.
Wall thickness:	$1\frac{1}{4}$ in.
Material:	stainless steel 316

2. Reactor Core

Active core height:	10 ft
Active core diameter:	10 ft
Reflector thickness:	2 ft

3. Primary Loop

Number of loops:	4
Size of loop:	24 in. (nom.)
Flow per loop:	15,250 gpm

4. Heat Transfer

Reactor Power:	850 MWT
Coolant:	sodium
Inlet temperature:	630°F
Outlet temperature:	1000°F
Coolant Flow Rate:	25.6×10^6 lbs/hr
Number of passes:	1
Maximum velocity:	28 ft/sec
Maximum fuel center temperature	1435°F
Average fuel center temperature	1143°F

TABLE OF REACTOR CHARACTERISTICS (cont.)

Engineering Data (cont.)

4. Heat Transfer (cont.)

Maximum tube surface temperature (outside):	1187°F
Average tube surface temperature (outside):	907°F
Axial peak/average power ratio	1.40
Radial peak/average power ratio:	1.05
Overall peak/average power ratio:	1.47
Coolant hot-channel factor:	1.17
Bed average volumetric heat generation:	52×10^6 Btu/hr-ft^3(15,200 $\frac{KW}{ft^3}$)
Core average volume heat generation:	1082 KW/ft^3 core
Coolant average pressure drop:	50 psi
Average specific power:	90.4 KW/kg U
Average heat flux:	4.5×10^5 Btu/hr-ft^2
Hot-channel outlet temperature:	1085°F
Maximum graphite center temperature:	1342°F
Required core pumping power:	1330 KW

U^{233}-LITHIUM-7-BeO THERMAL BREEDER

Under this concept the 100 μ granular fuel, a mixed oxide of uranium and thorium, in lithium, is maintained as a single continuous region as in the previous case. The reactor is cooled with lithium-7 and moderated with BeO. This reactor system is distinguished from the sodium cooled reactor in one important regard by the fact that the lithium-7 coolant has an activation product of very short half-life and, on this basis, little or no shielding of the primary loop is required. Accordingly, in order to prevent radioactive contamination from the fuel region, the design calls for an internal heat exchanger of a type which provides for complete separation of the fuel and the coolant. Since the BeO moderator would be compatible with lithium, no cladding is required and moderator maintenance would be reduced to a minimum, thereby allowing appreciable mechanical simplification of the internal heat exchanger and manifold system. With zirconium alloy coolant tubes the core, which is contained in a 10 ft. right cylinder, has a power output of 850 MW(t) and a conversion ratio greater than one. By using niobium instead of the zirconium alloy for the coolant tubes, the outlet coolant temperature could be increased and, as a result the same size core would be capable of a substantial increase in power output. However, the conversion ratio would suffer due to the higher cross section of niobium as compared with zirconium and would in all probability drop below unity.

<u>Reactor Mechanical Design</u>

The major design features of this Settled Bed Reactor are illustrated in Fig. 8. The plan view of the reactor shows the general arrangement of the moderator sections, side reflector, and fuel channels. The elevation view is sectioned in order to show some of the details of the coolant heat exchanger, bottom reflector, core tanks, reactor vessel, vessel supports, and other reactor components.

<u>Reactor Core</u>

The reactor core contains 28 unclad BeO moderator slabs arranged to form 14 parallel fuel channels. Each moderator slab is 5 ft. x 12 ft. x 7.2 in. Coolant tubes and fuel occupy the space between parallel moderator slabs. The equivalent core diameter is 10 ft. and the active core length is 10 ft. The core is completely surrounded by a 1.5 ft. BeO reflector.

As shown in the drawing, the eight coolant headers are located above the side reflector. Coolant tubes project from headers into the fuel channels and do not cross over the moderator slabs, thus permitting removal of the slabs by vertical withdrawal without disturbing other parts of the core. Similarly, each pair of coolant inlet and outlet headers and the associated tubing may also be removed by vertical withdrawal without disturbing other parts of the core. 1175 high temperature zirconium alloy U-tubes are required for each of the core quadrants. The U-tubes are 0.305 in. x 0.025 in., wall and are spaced on 0.505 in. equilateral triangular centers. There are three rows of tubes in each fuel channel. Spacers are used extensively to provide structural integrity in the heat exchanger tube bundles and assurance that the distances between adjacent tubes and between tubes and moderator surfaces are preserved.

The fuel consists of a settled bed of 100 μ ThO_2-UO_2 fuel particles in lithium. The fuel is introduced into the core in a fluidized state and fills the spaces between the coolant U-tubes and the moderator slabs. The method of fuel transfer or fuel addition is similar to the methods discussed previously for the sodium cooled reactor. There is provision for fourteen control rod thimbles, each located in the center of a moderator slab. This arrangement facilitates removal by remote means.

TABLE OF REACTOR CHARACTERISTICS

Engineering Data

1. Reactor Vessel

Design pressure:	75 psig
Design temperature:	1050°F
Vessel I.D.:	13 ft-3 in.
Vessel height:	18 ft
Wall thickness	$1\frac{1}{4}$ in.
Material:	zirconium alloy

2. Reactor Core

Active core height:	10 ft.
Active core diameter:	10 ft.
Reflector thickness:	18 in.
Moderator:	28 BeO rectangular slabs
Max. dimensions	5 ft. x 12 ft. x 7.2 in.
Coolant channel geometry:	4700 high temperature zirconium-alloy U-tubes 0.305 in. OD x .025 in. wall x 20 ft. Tubes are spaced 0.505 in. on centers in an equilateral triangular array.

3. Primary Loop

Number of loops:	4
Size of loops:	10 in. (nom.)
Flow per loop:	5,610 gpm

4. Heat Transfer

Reactor power:	850 MWT
Coolant:	lithium-7
Inlet temperature:	521°F
Outlet temperature:	1050°F
Coolant flow rate:	5.5×10^6 lbs/hr
Number of passes:	2
Maximum velocity:	40 ft/sec
Maximum fuel center temperature:	1484°F
Average fuel center temperature:	1125°F

TABLE OF REACTOR CHARACTERISTICS (cont.)

Engineering Data (cont.)

4. Heat Transfer (cont.)

Maximum tube surface temperature (outside):	1261°F
Average tube surface temperature (outside):	902°F
Axial peak/average power ratio:	1.33
Radial peak/average power ratio:	1.50
Overall peak/average power ratio:	2.0
Coolant hot-channel factor:	1.17
Bed average volumetric heat generation:	26.5×16^{6} Btu/hr-ft^3 (7,760 kw/ft^3)
Core average volumetric heat generation:	1082 kw/ft^3 core
Coolant pressure drop:	120 psi
Average specific power:	1393 kw/kg U^{233}
Average heat flux:	4.6×10^5 Btu/hr-ft^2
Hot-channel outlet temperature:	1140°F
Maximum moderator center temperature:	3450°F
Required core pumping power:	1205 kw

DIRECTLY COOLED FAST REACTORS

The two directly cooled fast reactors consist of core vessels containing the settled fuel beds of UO_2-PuO_2 or UC-PuC particles (up to $\frac{1}{4}$ in. diameter) through which coolant Na flows, intimately contacting the individual particles. One design calls for the coolant to flow axially through the reactor and the other design provides for radial flow. The core vessel is located in the main reactor vessel where it is completely surrounded by blanket beds of UO_2 or UC particles (up to $\frac{1}{4}$ in. diameter). The blanket beds are also directly cooled with Na. Bearing in mind the relatively high resistance for coolant flow through a bed of these particles in the settled state, the radial flow design would have the advantage of substantially reduced pressure drop as compared with the axial flow design. In the axial flow reactor, coolant Na is introduced above the settled bed and then flows downward through the bed, while in the radial flow reactors, it is introduced through the perforations in the walls of the inlet pipe located along the core axis and discharged to the blanket through perforations in the wall of the core vessel. The fuel and blanket beds are fluidized with Na to permit their introduction and removal from the reactor, as well as their redistribution within the reactor. The core heat output in the two cases varies from 822 to 838 Mw, and this is used to produce 300 Mw (e) net.

Axial Flow Directly Cooled Fast Reactors

The directly-cooled axial flow reactor core vessel (Fig. 9) consists of a 1-in. thick, 6.2-ft. O.D., and 5.75-ft. high 316 stainless steel tank with dished heads at both ends. A 1.5-in. thick perforated steel plate is provided to support the fuel bed. The perforations, half a particle diameter wide and several diameters long, total in area about half the cross sectional area of the plate. The plate and the core vessel are externally reinforced to support the weight of the fuel bed (approximately 20.5 tons). The core vessel is filled to an active height of 3.62 ft. and an active diameter of 6.03 ft. with the settled bed of 0.178-in. diameter spherical UC-PuC fuel particles. The fuel bed volume is 103.6 ft^3. The upper vessel space is provided for bed volume expansion during fluidization.

The main reactor vessel is made from 2-in. thick 316 stainless steel with overall dimensions of 9.5 ft. diameter and 12.75 ft. high. It is sealed top and bottom with dished heads. The entire vessel and bottom head are supported with external steel structural members. A structurally reinforced, 5-in. thick perforated steel plate (similar to the one described previously is welded into the bottom head section to support the blanket bed (approximately 78.6 tons). Pipes are welded to the two heads to provide slip fit connections with the 24-in. core coolant lines.

The reactor vessel is filled to an active height of 8.62 ft. and a 1.5-ft. radial thickness with a settled blanket bed of spherical UC particles. The bed occupies a volume of approximately 396.5 ft^3. Provision is made at the top to allow for bed expansion during fluidization. The core and blanket are filled and drained as described previously.

Directly Cooled Radial Flow Fast Reactors

The directly cooled, radial flow reactor core vessel (Figs. 10 and 11) consists of a 0.5-in. thick 316 stainless steel tank, ~ 4.0-ft. O.D. and 5.00 ft. overall height, with dished heads at both ends. A central 24-in. 316 stainless steel coolant feed pipe runs completely through the core vessel, and a 1-in. thick perforated steel plate provides support for the fuel bed. Perforations in the central coolant pipe and the core vessel wall are approximately half a fuel particle diameter wide and several diameters in length and provide flow area about half the total area. The bottom plate and the core vessel are externally reinforced to support the weight of the fuel bed (approximately 6.8 tons).

The core vessel is filled to an active height of 3.85 ft. and an active diameter of 3.85 ft. with a settled bed of 0.125-in. diameter spherical UC-PuC fuel particles. The fuel bed volume is 34.3 ft^3. The upper vessel space is provided for bed volume expansion during fluidization.

The main reactor vessel is made from 1.75-in. thick 316 stainless steel with overall dimensions of 6.93 ft. diameter and 13.75 ft. high. It is enclosed with dished heads at both ends. The vessel sides and bottom head are supported with external steel structural members. A structurally reinforced, 1.75-in. thick perforated steel plate (similar to the one described previously) is welded into the bottom head to support the blanket bed (approximately 49.2 tons).

The reactor vessel is filled to an active height of 8.57 ft. and 1.5 ft. radial thickness with a settled blanket bed of 0.125-in. diameter spherical UC particles. The bed occupies a volume of approximately 248.8 ft^3.

Primary coolant Na is introduced at both ends of the central pipe and flows radially through the perforated wall and the core and thence to the blanket bed where it is mixed with Na flowing downward through the blanket. The exiting Na from all parts of the reactor is removed through 8-in. pipes welded to the bottom reactor vessel head. Four 4-in. pipes serve as blanket fluidizing Na inlets. All other core vessel and reactor vessel connections are similar to those described previously. This reactor is filled and drained by the procedure described previously.

HEAT TRANSFER AND FLUID DYNAMICS

(Both Axial and Radial Flow Cases)

The limiting design condition for both reactors is the maximum allowable thermal stress on the individual fuel particles - 10,000 psi to UC and UO_2. UC-PuC, rather than UO_2-PuO_2, was selected as fuel because the thermal conductivity of the carbide is several times greater than that of the oxide, thereby permitting a substantially higher heat flux. However, one radial flow case using UO_2-PuO_2 fuel was briefly investigated and the results are included in the Table of Reactor Characteristics. The maximum pressure drop in the Na flowing through the bed was arbitrarily limited to 300 psi to permit the use of standard pumps and ordinary vessel design and construction requirements. The pertinent heat transfer core design data are presented in the Table of Reactor Characteristics.

The thermal stress in the fuel particles varies directly with the square of their diameter and with the volumetric heat generation rate, while the Na pressure drop through the fuel bed varies inversely as the 1.27 power of the particle diameter. A compromise has to be made, therefore, between thermal stress and pressure drop requirements. The calculated heat transfer coefficients using Na coolant are very high, and the resultant film temperature differences in all cases studied are only a few degrees. The average temperature difference between the fuel particle center and surface is in all cases calculated to be less than 47°F and the maximum calculated fuel particle center temperature is 1553°F.

TABLE OF REACTOR CHARACTERISTICS

A. Engineering Data

	Axial flow (height=diam)	Axial flow (height=0.6 diam)	Radial flow (carbide)	Radial flow (oxide)
1. Reactor vessel				
Design pressure,psi		350	350	
Design temperature,°F		1100	1100	
Outside diameter,ft		9.5	7.25	
Over-all height,ft		12.75	12.13	
Wall thickness,in.		2	1.5	
Material		A.I.S.I. 316 SS	A.I.S.I. 316 SS	
2. Reactor core vessel				
Design pressure,psi		350	350	
Design temperature,°F		1100	1100	
Outside diameter,ft		6.2	4.0	
Over-all height,ft		5.75	5.00	
Wall thickness,in.		1	0.5	
Material		A.I.S.I. 316 SS	A.I.S.I. 316 SS	
3. Reactor core				
Active diameter,ft	6.42	6.03	3.85	4.37
Active height,ft	6.42	3.62	3.85	4.37
Volume,ft^3	208	103.6	34.3	51.8
Composition				
UC-PuC(60%)	124.8	62.2	20.6	31.1
Na(40%)	83.2	41.4	13.7	20.7

TABLE OF REACTOR CHARACTERISTICS (cont.)

A. Engineering Data (cont.)

	Axial flow (height=diam)	Axial flow (height=0.6 diam)	Radial flow (carbide)	Radial flow (oxide)
4. Reactor blanket				
Radial thickness, ft	1.5	1.5	1.5	1.5
5. Primary cooling system, core				
Number of flow loops	1	1	2	2
Flow per loop, gpm	45,200	44,100	21,600	21,600
Size of flow headers, in.	24	24	24	24
Material of construction	A.I.S.I.316SS	A.I.S.I. 316 SS	A.I.S.I.316SS	A.I.S.I.316SS
Total pressure drop, psi	299	291	83.5*	61*
Total pumping power (at 70% efficiency), hp	11,260	10,750	3,010*	2,190*
6. Primary cooling system, blanket				
Estimated pressure drop, psi		5.44	45	
Estimated head required to circulate Na through bed, ft		15.05	125	
Estimated average flow velocity, ft/sec		0.27	2.09	

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*The total pressure drop, pumping power, and flow velocity values are for the core only. The pressure drop and pumping power for both core and blanket are about 50% greater, and the average coolant velocity through both core and blanket is about 25% lower.

TABLE OF REACTOR CHARACTERISTICS (cont.)

B. Heat Transfer

	Axial flow (height=diam)	Axial flow (height=0.6 diam)	Radial flow (carbide)	Radial flow (oxide)
1. Coolant material	sodium	sodium	sodium	sodium
2. Inlet temperature, °F	550	550	550	550
3. Outlet temperature, °F	1050	1050	1050	1050
4. Coolant flow rate, lb/hr	1.88×10^7	1.84×10^7	1.80×10^7	1.80×10^7
5. Number of passes	1	1	1	1
6. Average flow velocity, ft/sec	3.11	3.45	2.79*	2.35*
7. Average volumetric heat generation rate in fuel bed, Mw/ft^3 bed	4.03	8.09	24.0	15.9
8. Maximum volumetric heat generation rate in fuel bed, Mw/ft^3	13.8	26.2	49.8	34.2
9. Heat transfer surface, ft^2	36,100	25,150	11,770	14,900
10. Average heat flux, Btu/hr-ft^2	7.92×10^4	1.14×10^5	2.39×10^5	1.88×10^5
11. Maximum heat flux, Btu/hr-ft^2	2.74×10^5	3.70×10^5	4.95×10^5	4.04×10^5
12. Average fuel particle internal temperature difference, °F	27.3	30.8	46.3	43.6

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*The total pressure drop, pumping power, and flow velocity values are for the core only. The pressure drop and pumping power for both core and blanket are about 50% greater, and the average coolant velocity through both core and blanket is about 25% lower.

TABLE OF REACTOR CHARACTERISTICS (cont.)

B. Heat Transfer (cont.)

	Axial flow (height=diam)	Axial flow (height=0.6 diam)	Radial flow (carbide)	Radial flow (oxide)
13. Maximum temperature at center of fuel particle, °F	1553	1516	1176	1217
14. Maximum thermal stress on particles, psi	10,000	10,000	10,000	10,000
15. Maximum-to-average radial power peaking factor 1.86	1.86	1.85	1.19	1.22
16. Maximum-to-average axial power peaking factor	1.48	1.41	1.40	1.41
17. Over-all power peaking factor	2.75	2.60	1.66	1.72
18. Factor to compensate for local variations in heat transfer coefficient over particle surface	1.25	1.25	1.25	1.25
19. Average core power density, kw/liter core	142	286	849	561
20. Average specific power in fuel, kw/kg Pu	258	497	1000	887

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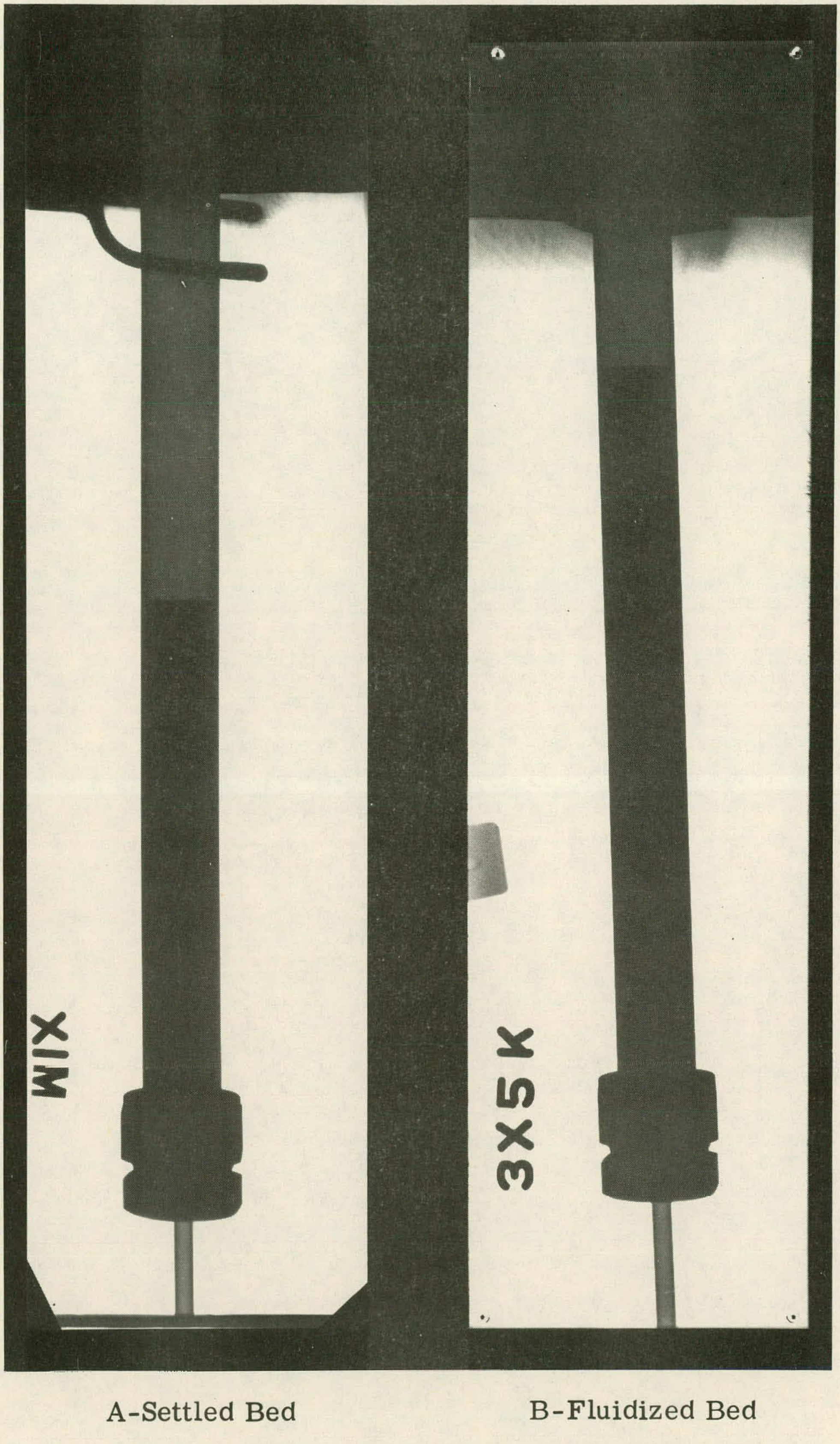
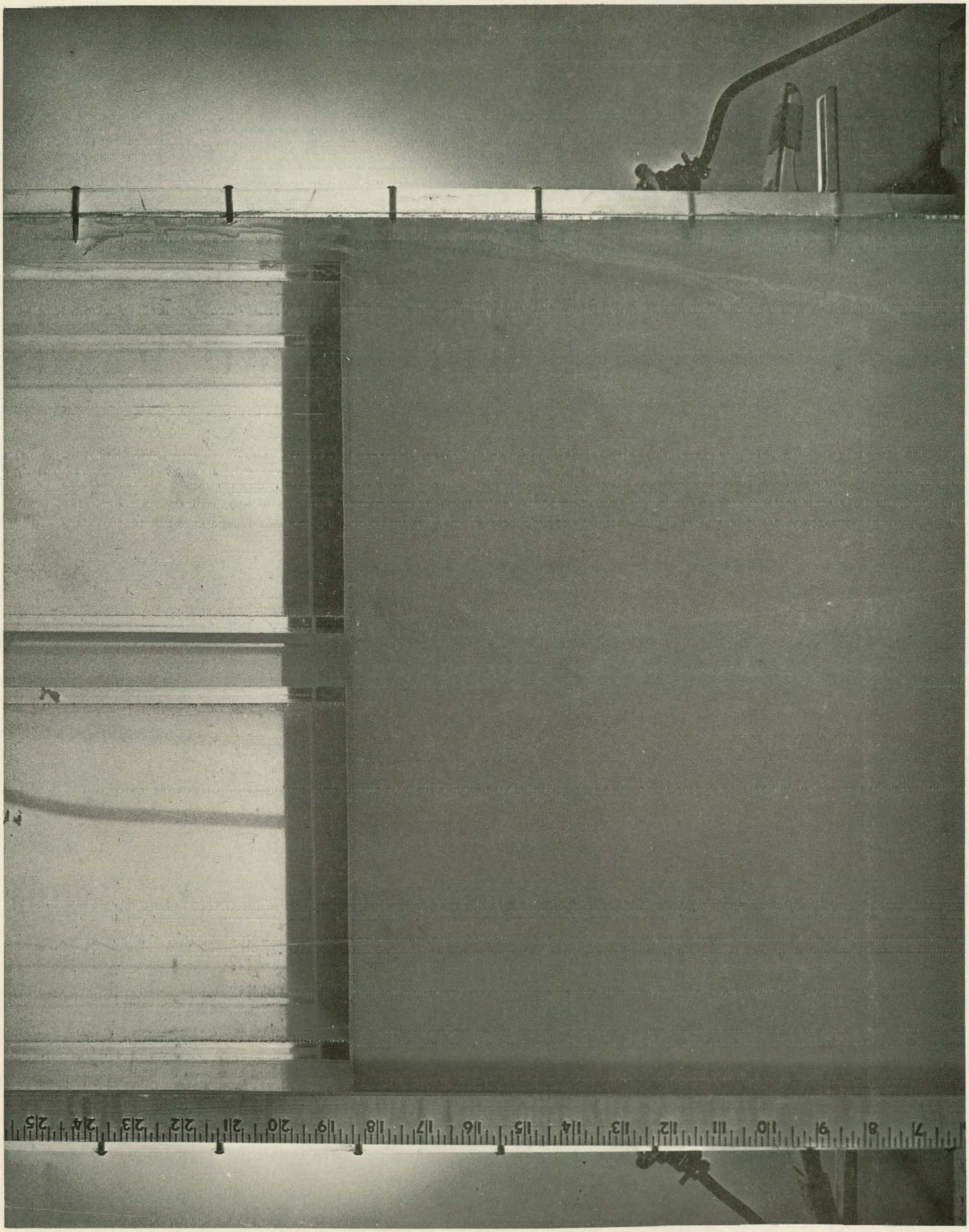


A-Settled Bed B-Fluidized Bed

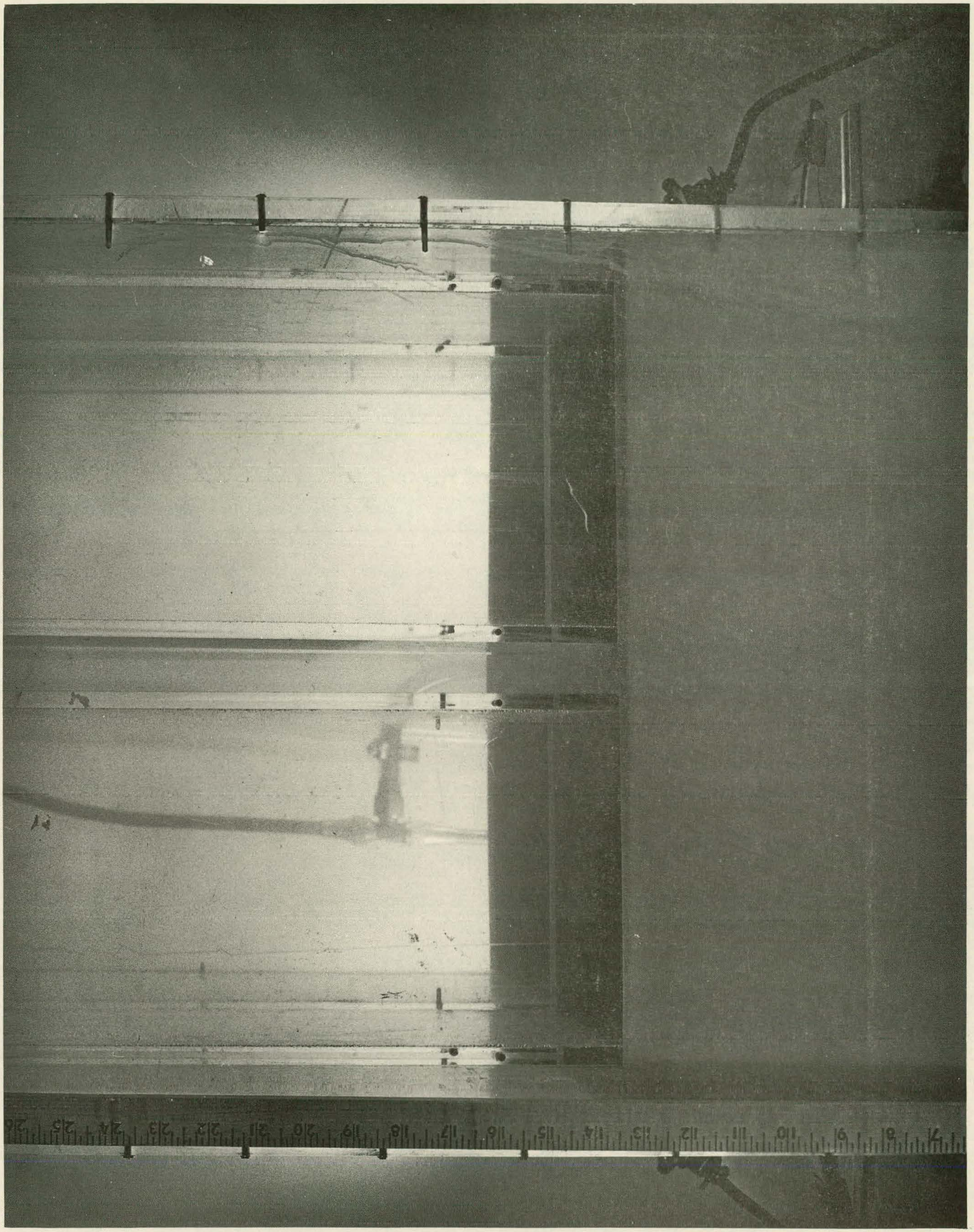
Radiographs of a UO_2-NaK Fluidized Bed

FIG. 1



Experimental Particulate Fuel Mockup showing the bed in the fluidized state.

FIG. 2



Experimental Particulate Fuel Mockup. In this view the bed is settled.

FIG. 3

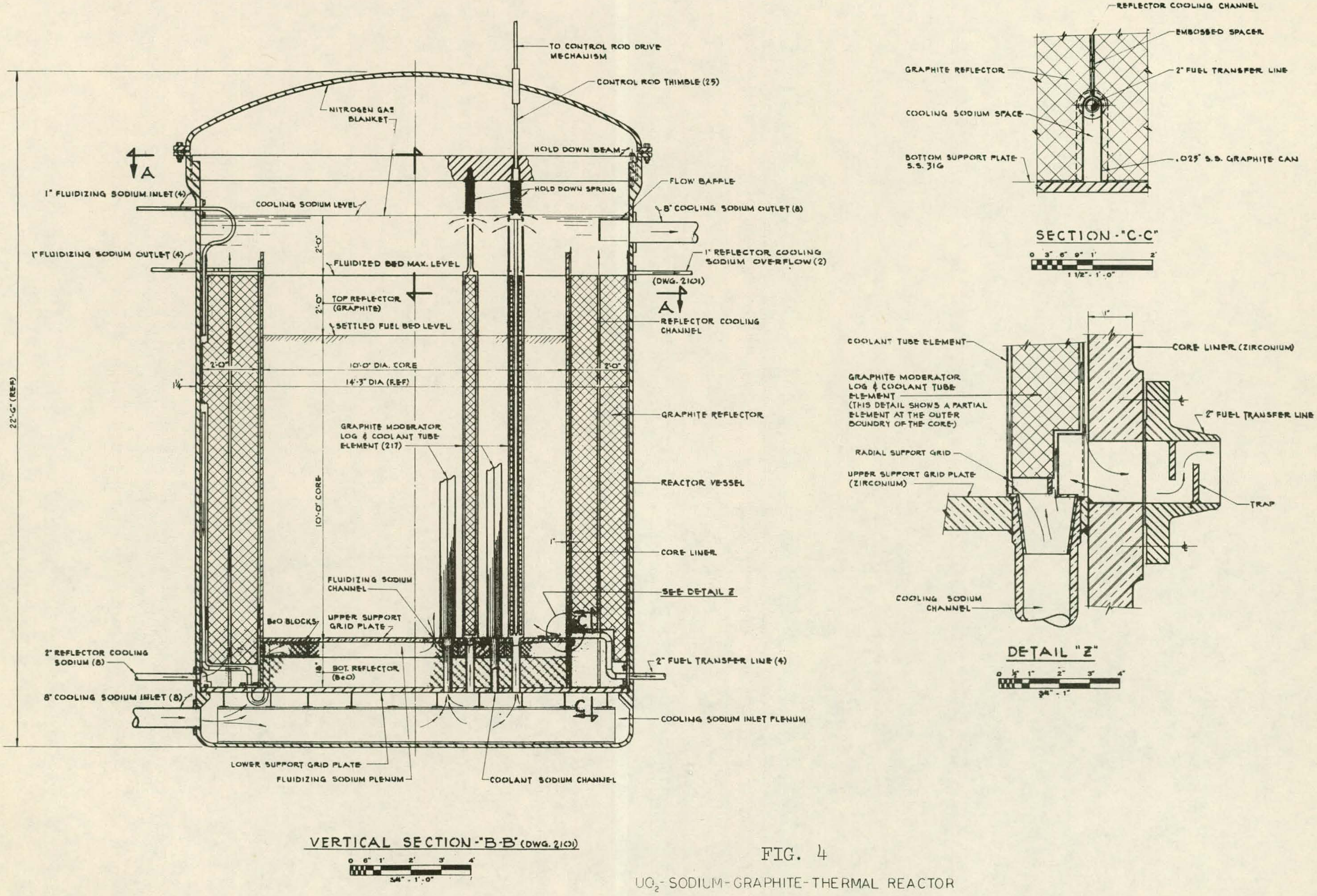
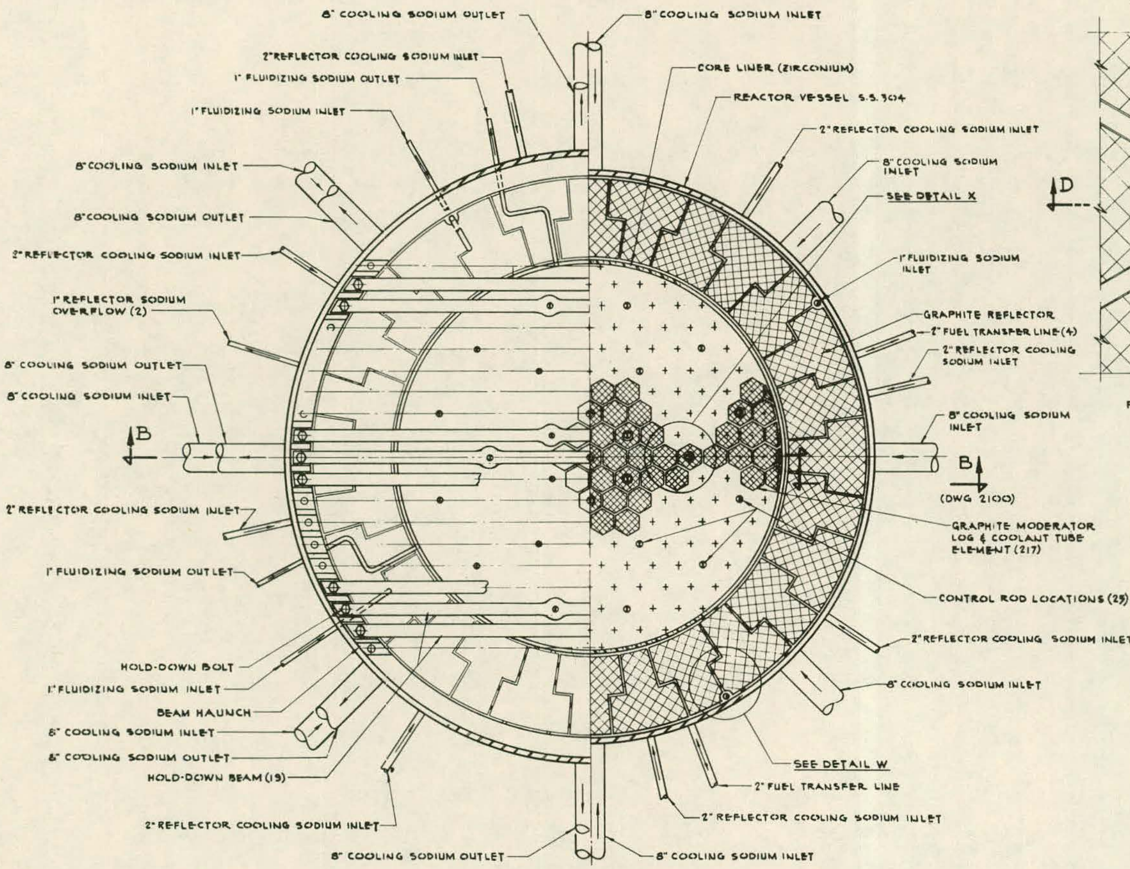


FIG. 4

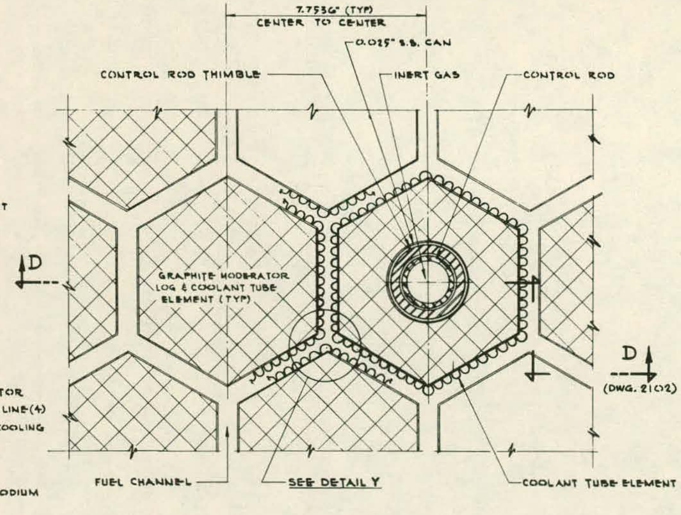
UO_2- SODIUM-GRAPHITE-THERMAL REACTOR

605 31



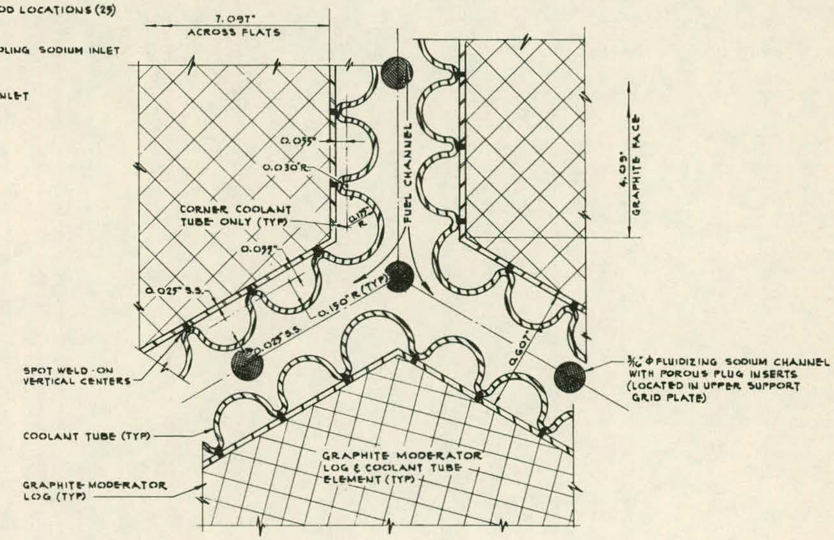
HORIZONTAL SECTION-"A-A" (DWG. 2100)

3/4" - 1'-0"



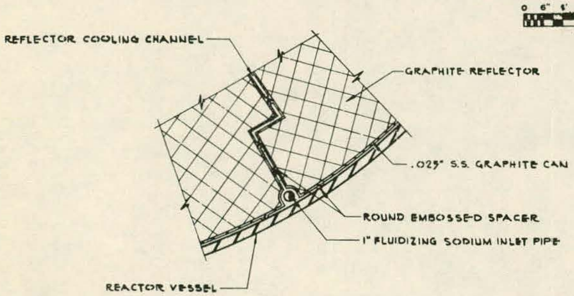
DETAIL-"X"

1/2" - 1"



DETAIL-"Y"

4" = 1"



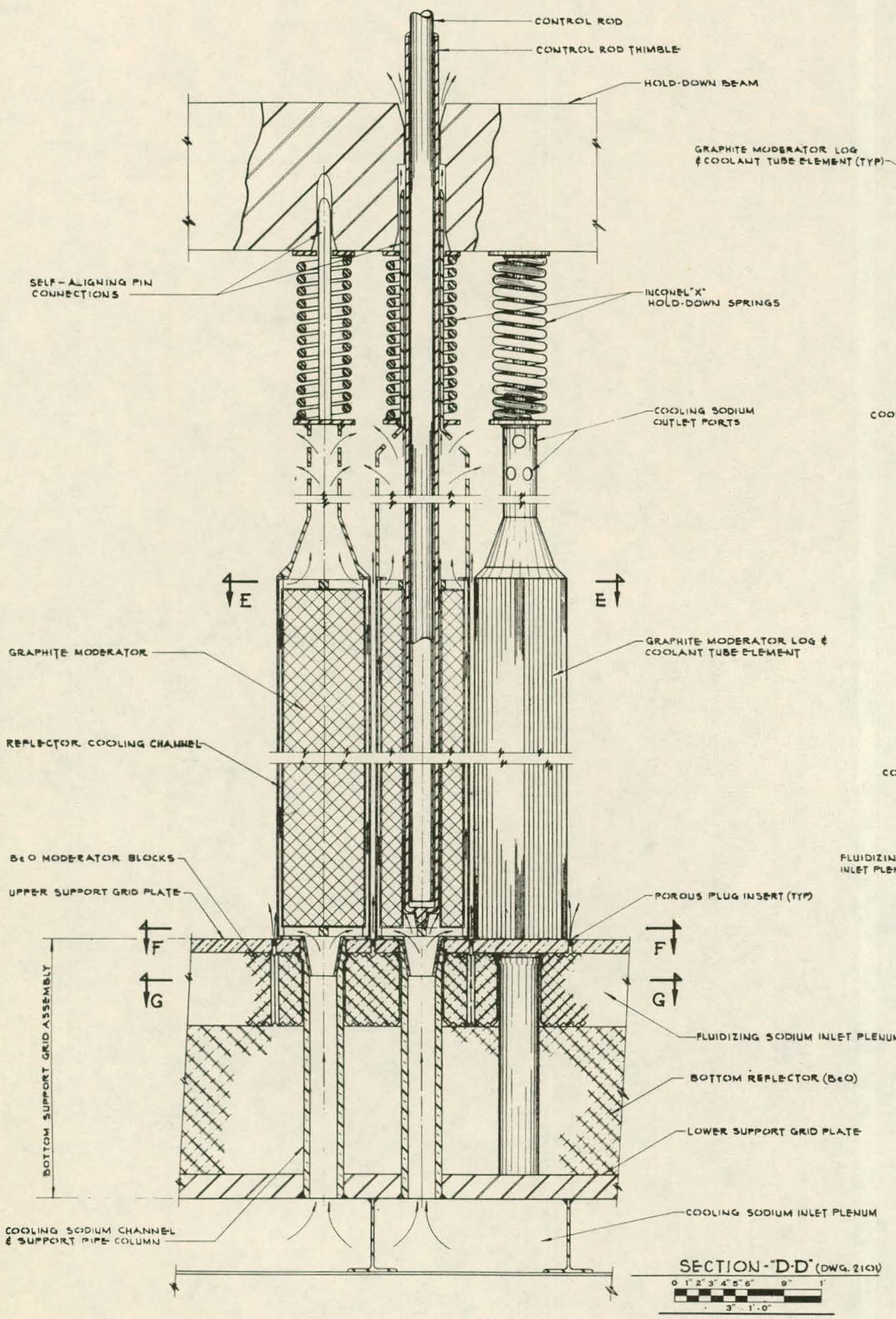
DETAIL-"W"

1 1/2" - 1'-0"

FIG. 5

UO_2 SODIUM GRAPHITE THERMAL REACTOR

605 32



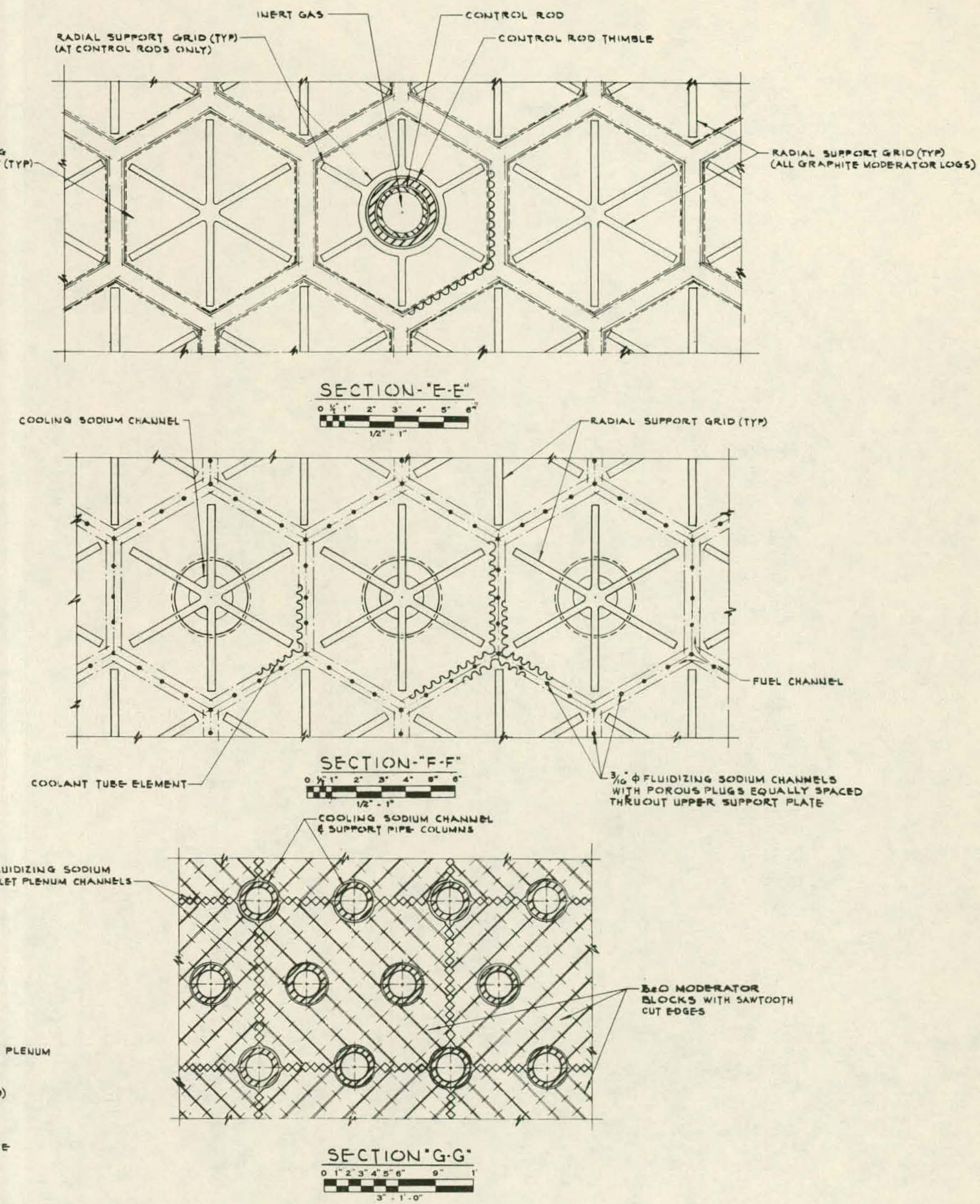


FIG. 6

UO_2- SODIUM-GRAPHITE-THERMAL REACTOR

605 33

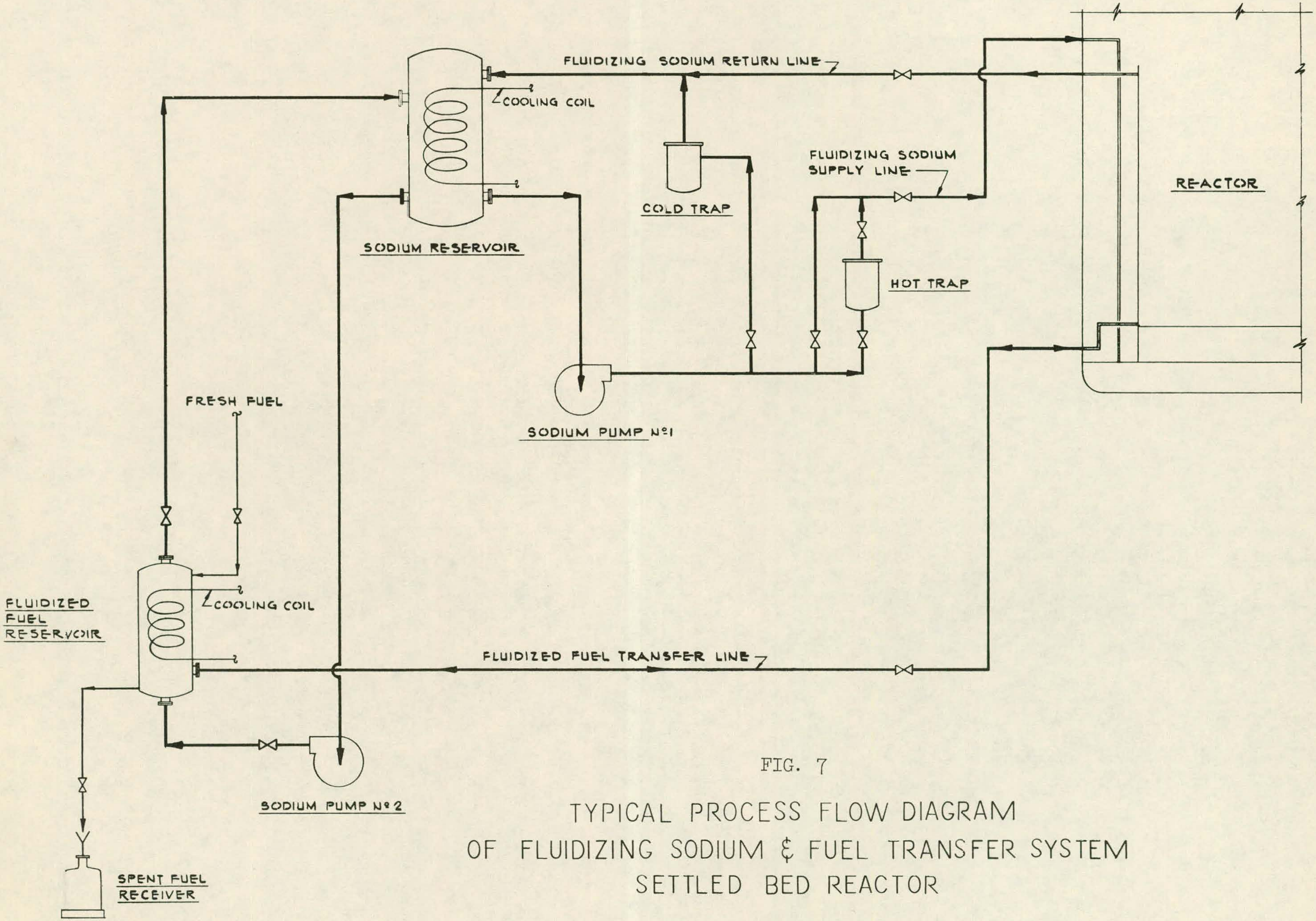


FIG. 7

TYPICAL PROCESS FLOW DIAGRAM
OF FLUIDIZING SODIUM & FUEL TRANSFER SYSTEM
SETTLED BED REACTOR

605 34

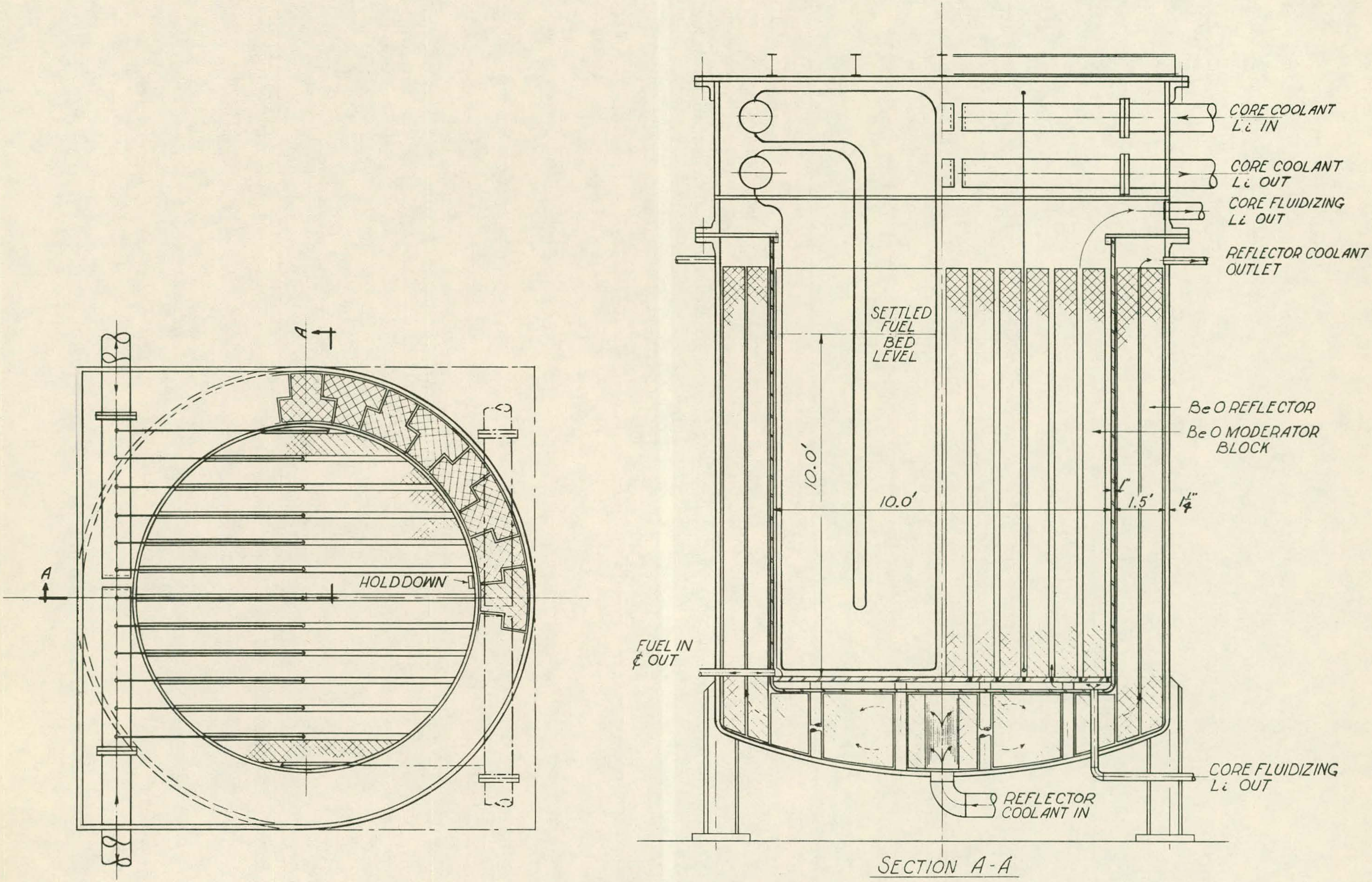


FIG. 8

U_{233} - Li^7 - BeO THERMAL BREEDER

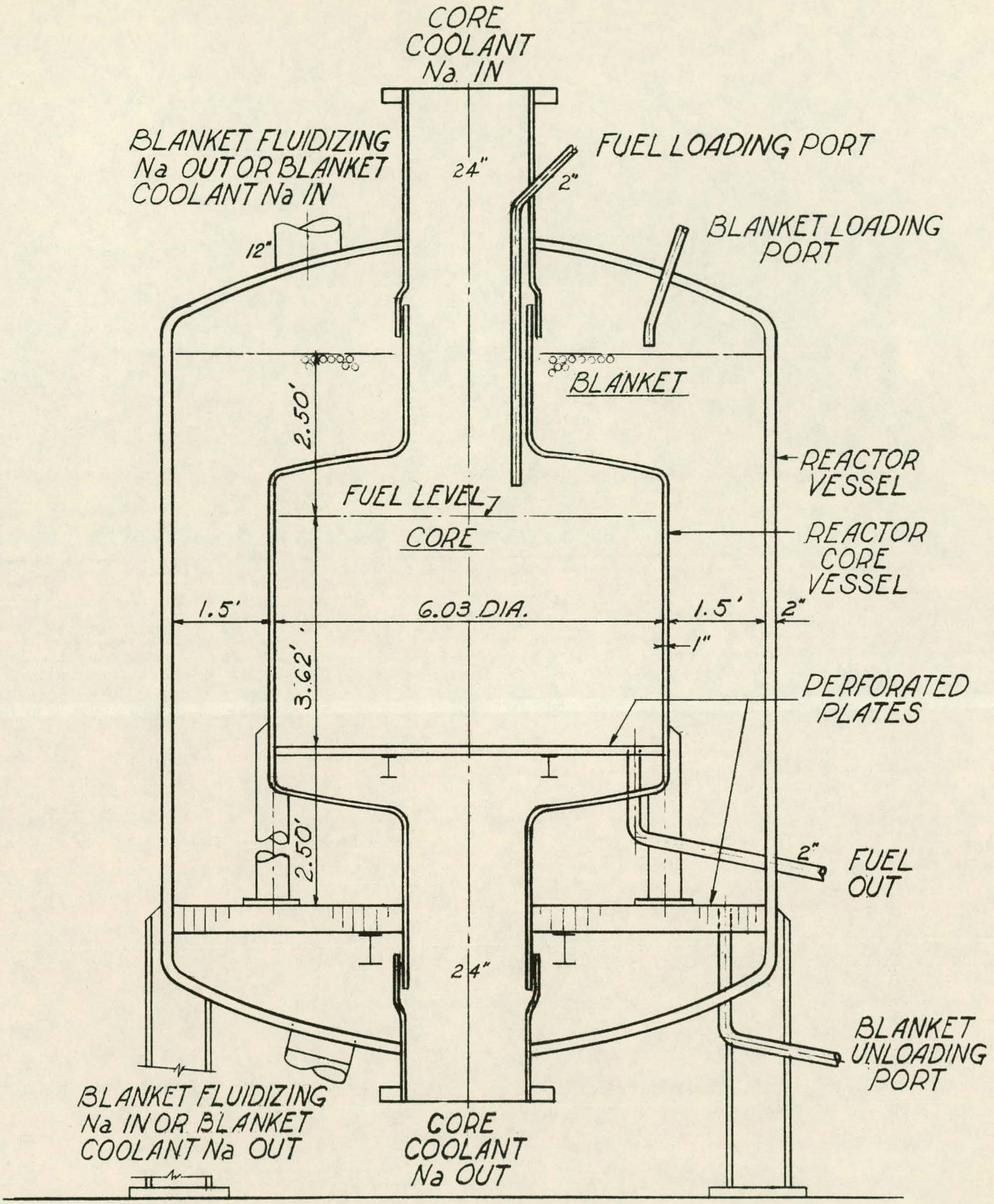


FIG. 9

SODIUM COOLED FAST BREEDER REACTOR
AXIAL FLOW TYPE

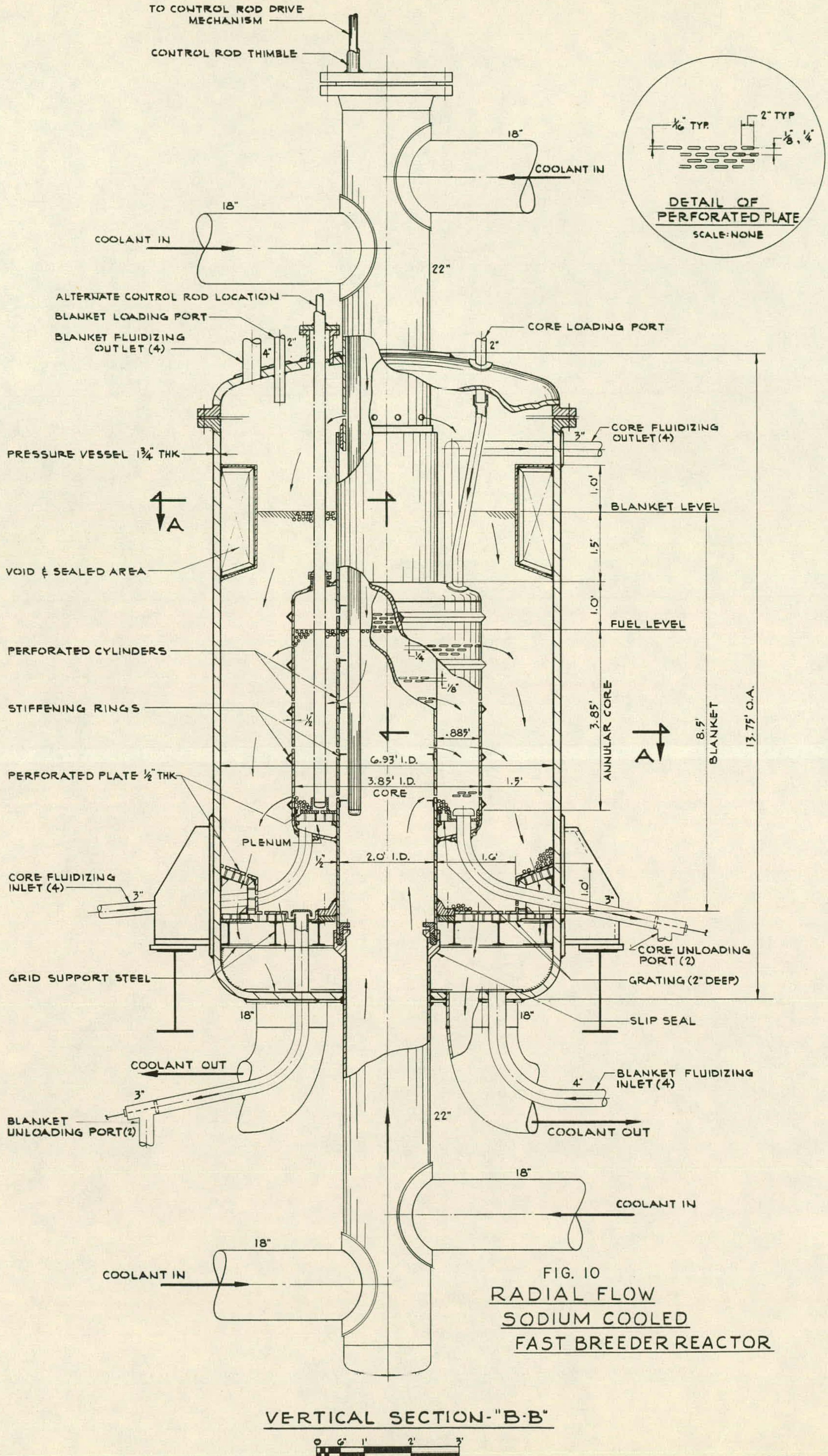
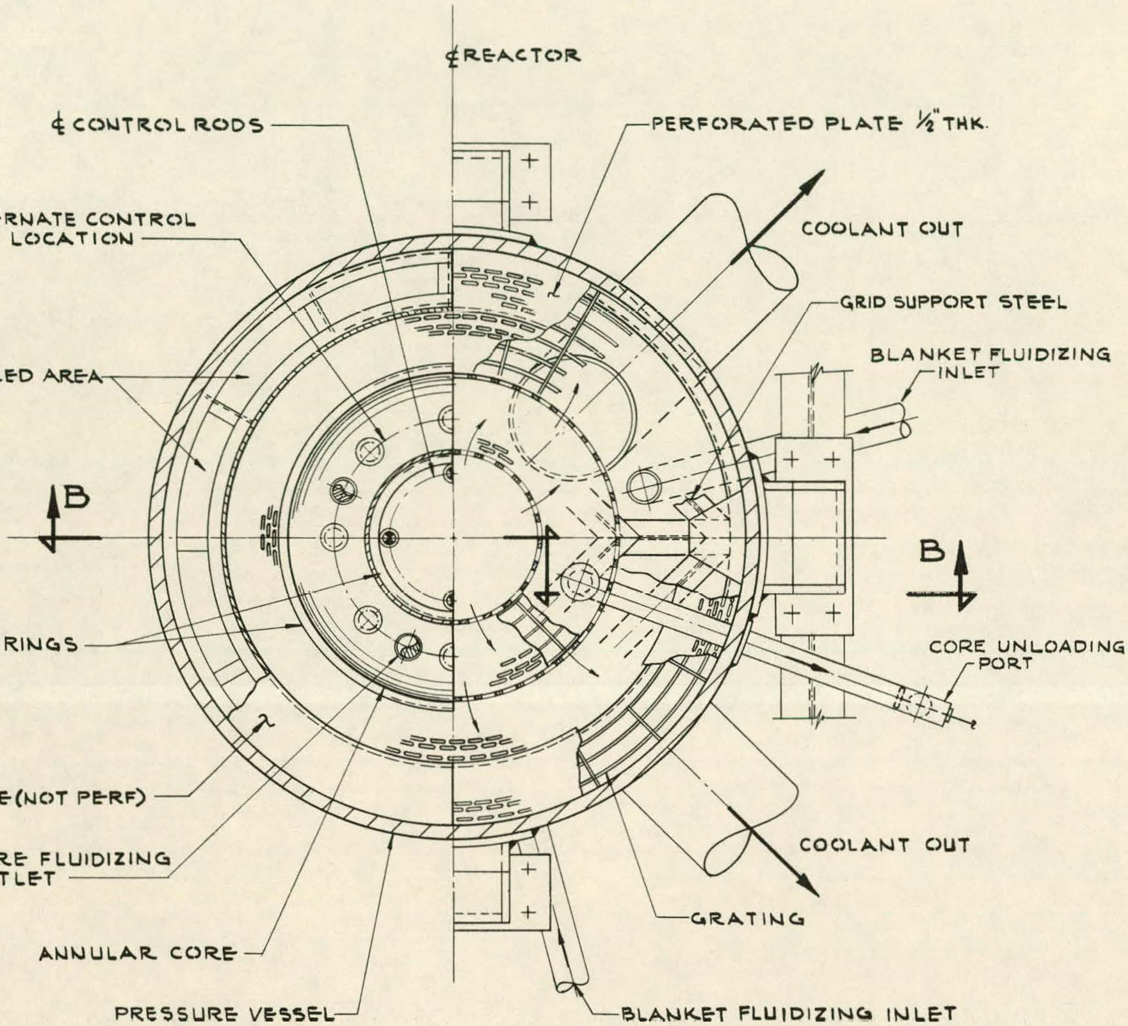


FIG. 10
RADIAL FLOW
SODIUM COOLED
FAST BREEDER REACTOR

VERTICAL SECTION-"B-B"



HORIZONTAL SECTION - "A-A"

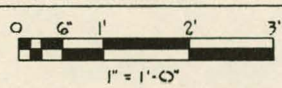


FIG. 11

RADIAL FLOW SODIUM COOLED FAST BREEDER REACTOR