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CENTRAL STATION FAST BREEDER REACTOR PLUTONIUM FUEL REQUIREMENTS *)

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ABSTRACT

Some basic decisions on fuel and pin type introduce into the field of the principal criteria for the fuel of large fast breeder reactors, which are presently in a conceptional stage. These criteria comprise the questions of safety and economy and refer also to the applicable fabrication techniques. As the German development program pursues in parallel the two lines of a sodium cooled fast breeder and a steam cooled version, the fuel pin requirements are compiled for both cases. The comparison of the two concepts underlines some principal common conditions. A few very marked differences however - especially the quite different external pressure load from the cooling medium - suggest a specifically adapted layout. The pin layout characteristics, proposed in detailed reference designs, translate the principal requirements to real designs and also to fuel and pin specifications. These important consequences of the basic ideas are discussed in the light of present knowledge and fabrication know-how. The realistic fabrication possibilities and the available experience on oxide pin performance lead to serious limitations, e.g. considering the radial swelling problem. In conclusion the future development lines concerning fuel types and pin features are shortly mentioned and compared to possible future fuel requirements.

INTRODUCTION

The fast reactor fuel requirements are evaluated in different stages of development. In the German fast breeder program the first stage was dedicated to some principal selection studies, a procedure, which of course is typical for all large technical development projects. As a first basic decision, oxide type fuel for the fast breeder prototype reactor designs was selected. A metal fuel was considered to be too limitating with respect to the necessary linear power rating at high fuel temperature and to the achievable burnup. On the other hand carbide ceramic is not yet enough experienced, at least not within the available technological know-how for our project. A second approach, however, may be performed with carbide fuel leading to an economically improved fuel cycle.

A further basic decision pertains to the external and internal geometry of the fuel arrangement. Having also studied the feasibility of ball-shaped fuel units, we selected pin type geometry, the latter being more evaluated, both in the inpile cooling behaviour and in the fabrication techniques. The internal geometry is conventional. As we propose a tight free standing strong can, provisions are to be made for the fission gases and vapors and also for the solid fuel swelling in radial and axial direction. Thus the total length of the fuel pin is distributed to the active fuel zone, to lower and upper axial blanket regions and to a fission gas plenum.

The design ideas for fast reactor fuel pins are strongly oriented to our fast reactor design studies for a sodium cooled prototype reactor[1,2,3] and a steam cooled prototype[4]. There might be some differences between prototype designs and future central station fast reactors with a capacity of, say, 1000 MWe, mainly concerning the enrichment in fissionable isotopes and the pin length. These differences are considered to be of minor influence to the overall performance of the pin type fuel and hence can be neglected in this state of evaluation. The design principles follow a rather conservative line as far as preparational assumptions for a pin layout are concerned. They are based on some irradiation test pin layout experience[5], on the single efforts of our fuel development program[6] and also on our irradiation performance considerations and results[7].

The paper here describes at first the basic criteria, which are the starting point for the pin design logic. These lead to the fuel pin requirements for prototype fast reactors. The requirements have to be translated to detailed wording within specifications, some highlights of which we are presenting in the chapter on pin layout characteristics, together with a few typical drawings. In conclusion, there is a discussion on the main limitating factors for a pin layout and on possible future and futuristic development lines.

It should be mentioned, that the requirements concerning the whole subassemblies bring certainly some important enlargement, which refer mainly to the cooling thermodynamics. As the subassembly features are only of minor influence to the pure fuel and fuel pin technique, they are not included here. Above that such subassembly requirements are not yet in a stage of technical evaluation as to be easily expressed in common principles.

BASIC CRITERIA

The basic criteria for the fuel pin design have their sources in the triangle: safety, economy and breeding potential. A forth point of view, which is less scientific - but is of practical importance - is the adjustment to the available development background. The following paragraphs will outline, in more detail, these considerations.

The safety criteria refer to normal reactor operation conditions, if they ask for duly adapted smooth linear power rating distribution. They refer also to possible sudden overpower conditions in the reactor core, when reactivity changes must be outruled by inherent safety features. Their wording might be in short terms:

- The fuel specifications concerning the longitudinal distribution of fissionable material are to be established as to guarantee a smooth heat source distribution over the pin length according to the requirements for the hot channel analysis of the subassembly.

- The reactivity feedback according to an - expectedly - negative temperature coefficient for the Doppler effect in the fuel mixture must become effective within calculated short delay time in a reactor power transient. This asks for specified homogeneity in the plutonium distribution. In this context reference is made to a recent theoretical work[8].

- Another limitation is induced by the socalled "slumping danger". The internal geometry of the fuel pin has to limit axial fuel movement to a specified extent, in order to avoid inherently fuel configurations, which produce an uncontrollable reactivity increase. A general measure in this context is to limit the free volume in the fuel ceramic. This leads to a lower limit for the smeared density of the fuel.

The economic criteria receive their language from different aspects concerning the fuel cycle:

- A plain, but most important truth is, that the fuel pin specificationsare to be established as a fit to the whole fuel cycle in an optimized manner.

- There are special limitations due to the fact, that the source material market and prices are not yet developed. Hence the fuel pin requirements get an incentive to proceed in a direction of the "least amount of fuel in the fuel cycle", which may not be the cheapest way.

- Another criterion spells out, that the fuel pin production must be possible at dates according to the time schedule of the prototype planning. Hence the specifications take consideration of the really available techniques and the really foreseeable price situation[9].

- Finally a principle of continuous evolution demands, that the initially established specifications are also applicable to recycle fuel without major economic influence. This means for instance, that a fuel fabrication line, which is adjusted to a set of specifications, can handle also plutonium of equilibrium isotopic composition.

The breeding potential as a target is implicitly involved in the economic criteria. Above the pure economic optimization, however, there is an additional special incentive:

- In order to make comparable the "doubling time" of the future expanding energy demand to the doubling time of an expanding breeder reactor population, a high breeding potential is a separate criterion for the reactor design. Hence the fuel layout via the internal breeding ratio is directly affected. In this context belong also the evaluations - presently underway - for a pure uranium startup with U 235, in order to soften the conditions of a "dry" plutonium market.

The basic selection criterion with respect to available experimental and technical experience reads e.g. as follows:

- A fuel pin design for a large fast breeder reactor can be based reliably only on a sufficient fabrication experience - at least in pilot plant scale - and on the positive results of irradiation performance tests with a number of pins, which allow at least some statistical judgement.

FUEL PIN REQUIREMENTS FOR PROTOTYPE DESIGNS

The elements of the fuel pin requirements are getting their incentives and limitations by

- reactor physics
- fuel cycle economics
- safety considerations

Taking also into account the basic criteria formulated above, these requirements are outlined and discussed in the following statements.

The enrichment of fissionable material is dictated by the core magnitude and the detailed core design. The content in fissionable Pu is for large fast oxide breeders in the range between 10 and 25 % of total U and Pu contained in the fuel. Normally two radial zones different in the enrichment are provided in order to get a radial power flattening. For a 1000 MWe sodium cooled design e.g. the figures are about 10 % in the central zone and 14 % in the outer zone, while at typical prototype designs (ca. 300 MWe units) the contents are 15 and 23 %, respectively.

The isotopic composition of the plutonium itself will correspond in the long term range to the related equilibrium conditions of the fuel cycle. At combined core and blanket reprocessing management, there might be a composition of, say, 75 % Pu 239, 22 % Pu 240, 2 % Pu 241 and about 1 % Pu 242. At a separated reprocessing routine the content of higher Pu isotopes in the core cycle will be much higher, of course.

The linear rod power is selected to have values which guarantee no central melting of the fuel. Hence at nominal conditions the maximum figures are in the region of 500 watts/cm. These are the data, which are typical for sodium cooled fast reactors. At the steam cooled version the economically reasonable surface heat transfer makes further limitations to bring the maximum nominal rod power into the range of 350 watts/cm at still reasonable diameters.

The fuel diameter at sodium cooling is determined by the optimized rating value and the selected rod power. At steam cooling the diameter is a compromise between the incentive to a large rating, the feasible steam cooling technique and an economically favoured increased diameter. In both cases the region between 5 and 6 mm in fuel diameter is the result of recent reference design evaluations.

The length distribution of a pin is governed by the request for axial breeder blankets and a fission gas plenum. The volume demand of the latter is in strong relationship to the mechanical pin concept and the internal fuel geometry, see below.

The internal breeding ratio receives its "sources" only from fertile material in the core. Therefore the highest allowable fuel density - each additional density percent is of full benefit to the fertile potential - is aimed for.

The smeared fuel density is a compromise between the necessary porosity in the ceramic body for gaseous and solid fission products - which defines the higher density limit - and breeding loss as well as the slumping danger concerning the lower limit. The most promising density range for oxide type fuel is -

according to our knowledge - between 80 and 85 % of theoretical density. For first core equipment of prototypes we propose to use 80 % of theoretical density taking into account a sacrifice in internal breeding. It is hoped that further irradiation performance experience will justify a moderate fuel density increase for later central station fast reactor fuel pins.

The fuel burnup is expected to be in ranges between 50 000 and 100 000 megawatt days per metric ton of heavy elements. A steam cooled reactor might have the schedule at about 60 000 MWd/ton, while a sodium cooled prototype asks for 80 000 to 90 000 MWd/ton, all expressed as maximum burnup values. The requirements for future large central stations may be still somewhat higher.

The level of the cladding temperature distribution is forced to the highest possible data by the required thermal efficiency of the system. The maximum nominal can midwall temperature is about 600°C for sodium cooling and about 650°C for steam cooling.

The mechanical requirements onto the pins are outlined by the strong can concept. For sodium coolings the necessary mechanical properties are defined by the fission gas pressure buildup during burnup and the thermal stresses in the can wall. The radial solid fission product swelling is considered to be the most dangerous mechanical attack to the cladding wall. The pin lifetime is solely governed by these impacts, if the cladding material layout is to withstand the fission gas and thermal stresses for the expected loadtime at fast neutron environment. Hence the mechanical cladding layout is to be adjusted to the available swelling volume for the solid fission products.

For steam cooling the pressure situation with respect to the cladding is turned around. The high coolant pressure outbalances by far the internal gaseous pressure within the pin. This situation is accompanied by the mechanical creep buckling problem. This instability danger must be handled by additional tubing specifications in high temperature creep strength and in initially limited ovality and also by possible internal support from the ceramic fuel. For steam cooling the "strong can" thinking has lost some of the absoluteness.

The internal geometry of the pin has two main sources of definition. The first one deals with the homogeneity of the fuel mixture. Due to the fact that the inherently acting negative Doppler coefficient shall operate instantaneously, the largest admissible pure PuO_2-particles are in the magnitude of 100 micron. Above that microhomogeneity, there is a request for "macrohomogeneity" in the fuel, which means an overall uniform distribution of the fissionable isotopes in the fertile matrix.
The second source of definition is embedded in the upper and lower density limits, see above. The chosen smeared density can be realized by different fuel densities (for pellet fuel), corresponding to a proper amount of open voids for gap, dishing and central hole. The gap between pellet surface and can, diametrally about 100 to 200 microns, provides for thermal expansion and some fission product swelling. It favours also the pellet fill-in steps at the pin production. According to our knowledge, there is no special incentive for pellet dishing and central hole from the irradiation performance standpoint, if the rod power is high enough to plasticize the central fuel region. The fabrication procedure, however, in some cases may prefer a dished or cored pellet, in order to direct the bulk density of the pellet into higher ranges, where sintering precision is easier to be controlled.

PIN LAYOUT CHARACTERISTICS

In this paragraph it is intended to summarize all actual information concerning the real pin layout. Of course the main examples are taken from the reference design studies[1,2,3,4]. Other to some extent very representative examples can be derived from the layout characteristics for pin irradiation performance tests like the fuel irradiations in the Enrico Fermi Fast Breeder Reactor (EFFBR)[5] and the pin irradiation in a trefoil rig of the Dounreay Fast Reactor in Scotland. All important data are compiled in Tables I and II. There was made a distinction between performance parameters and fabrication parameters. The latter ones constitute the network of pin specifications, while the first ones show the operational conditions in the reactor core or in the irradiation test bed.

The pin layout data for the Na1 reference design are somewhat futuristic, mainly in the expected maximum burnup compared to the assumed smeared fuel density. The Na2 reference design concentrating now to a prototype reactor of 300 MWe capacity takes more cautious parameters on the basis of very conservative solid fission product radial swelling calculations. The D1 reference design for steam cooling outlines an evaluation comparable to the Na1 stage. The D2 design for the steamcooled prototype, which is presently under evaluation, is not yet included here. There are three examples for irradiation test pins. The two data sets for EFFBR specimens include both a pellet pin version and a pin with vibrocompacted powder fuel. The specimens for the DFR irradiation finally are more developed to a conservative pin layout.

A demonstration of the pin layout in simplified drawings is included in Fig.1 for the reference design pins and for the irradiation test pins. Hence the main geometrical features can be compared.

MAIN LIMITATIONS AND FUTURE DEVELOPMENT

As to the present status of experience we see the main limitations for a high performance oxide fuel pin layout in the radial swelling problem and in the hardly sufficient high temperature creep behaviour of the cladding material. Especially at a steamcooled fast reactor the high external pressure may cause a mechanical instability by creep-buckling.

If a conservatively low smeared density for the fuel is taken - in order to provide voidage for the solid fission products - the slumping danger arises. Also the internal conversion ratio is adversely affected. One of the goals of future systematic experimental evaluations is to find the fuel density, just highest possible in view of radial impact on to the cladding. This density figure, of course, will be dependent on a network of parameter constellations like internal fuel geometry, temperature distribution, cladding restraint and burnup level.

The fission gas pressure buildup is partly governing the mechanical analysis of the cladding. But principally in all cases the fission gas plenum can be foreseen large enough, as to shift the critical path for the cladding design to other claims like thermal stresses or radial swelling forces. Therefore the concept of fuel venting get the justification only from space availability arguments, because the pin geometry with fission gas plenum reduces the axial blanket amount.

The ceramic fuel of the mixed carbide and nitride type is considered to be of remarkable potential for future pin designs. The high heavy metal density is of sensitive benefit to fuel cycle economy, as the breeding ratio is favorable influenced and a higher fuel rating is possible. This trend is fully on the line of future fuel requirements. After the present development efforts, which are mainly directed to specify a uniform production, to investigate the compatibility to cladding and to overcome the large fission product swelling, there may be some switchover from oxide to these new fuels.

A further field of urgently necessary development is with the tubing material and technology. New alloy types for sodium cooling, as e.g. the vanadium base alloys, are under investigation. But also the class of iron base alloys, the steels, need a "tailor-making" procedure, as the bulk of the now available steels were not developed for reactor design requirements. Especially the fast neutron induced irradiation damages ask for new "streamlined" steel alloys.

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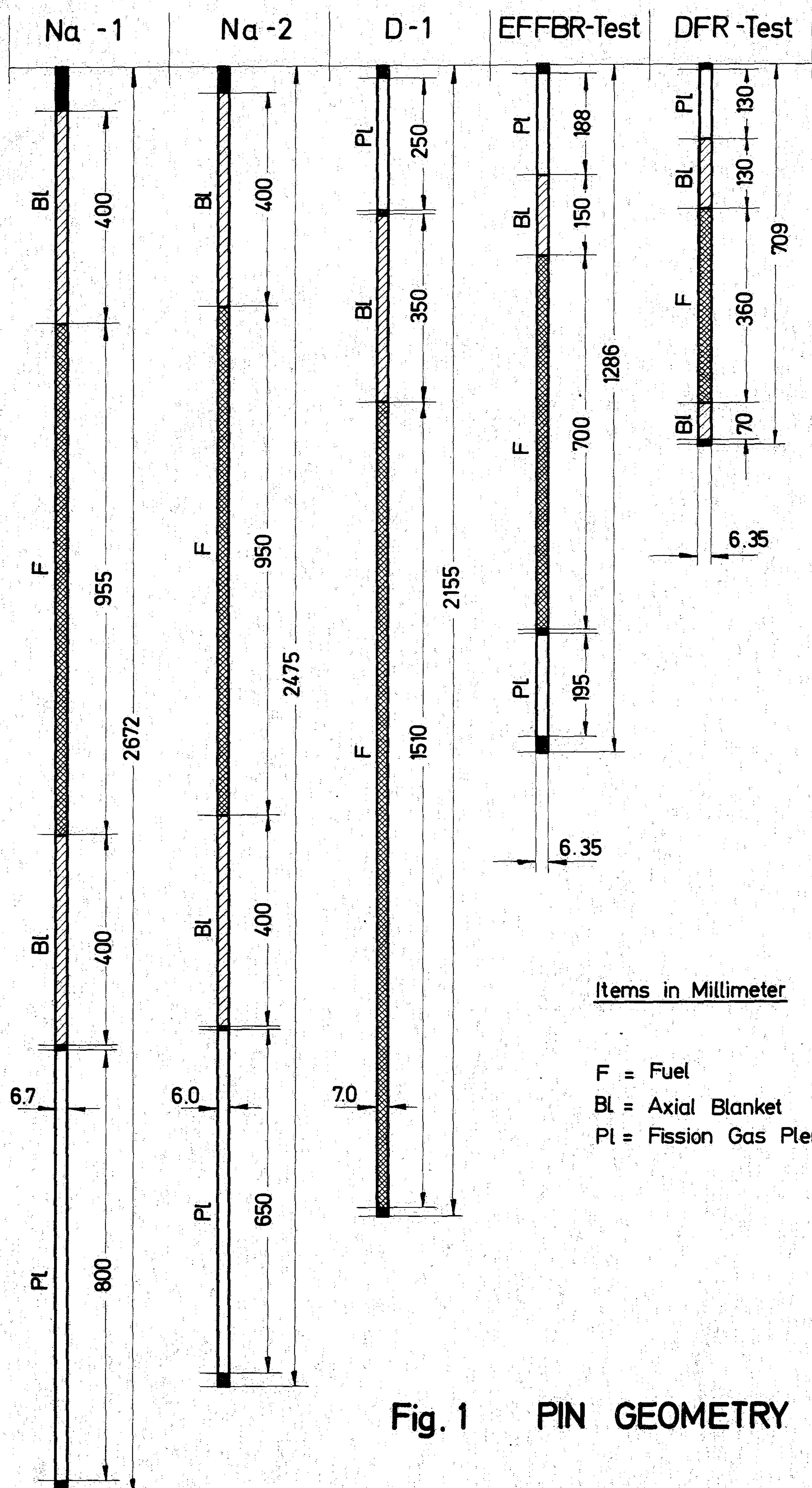
Table I PIN LAYOUT FOR REFERENCE DESIGNS

		Parameter	Unit	Na-1 Design (1000 MWe, sodium-cooled)	Na-2 Design (300 MWe, sodium-cooled)	D-1 Design (1000 MWe, steam-cooled)
Operation		Max. Linear Rod Power, nominal	(W/cm)	566	446	326
		Max. Can Midwall Temp., nominal	(^{o}C)	625	627	622
		Max. Can Midwall Temp., hot spot	(^{o}C)	654	696	737
		Max. Internal Gas Pressure	(atm)	70	70	260
		Max. External Pressure	(atm)	4	6	170
		Max. Burnup, axially averaged	(MWd/t_{Metall})	100 000	68 000	55 000
Fabrication Parameter	External Geometry	External Diameter	(mm)	6.7	6.0	7.0
		External Length	(mm)	2672	2475	2155
	Internal Geometry	Wall Thickness	(mm)	0.35	0.38	0.37
		Diametral Gap	(μ)	-	140	180
		Upper Axial Blanket Length	(mm)	400	400	350
		Fuel Length	(mm)	955	950	1510
		Lower Axial Blanket Length	(mm)	400	400	(separate)
		Fission Gas Plenum Position		Bottom	Bottom	Top
		Length	(mm)	800	650	250
	Cladding Material			Incoloy 800	16/13 CrNi	Inconel 625
	UO_2-PuO_2-Fuel	Fuel Shape		Vibro Powder	Pellet	Pellet
		Composition in Zone 1/2	(w/o PuO_2)	16/20	20/30	13/16
		Smeared Density	(% th.d.)	90	80	87
	UO_2-Blanket, Smeared Density		(% th.d.)	90	90	87
	He Filling, initial pressure at room temp.		(atm)	1	1	56

Table II PIN LAYOUT AT PERFORMANCE TESTS

			Test Irradiation in EFFBR: Pellet Fuel	Test Irradiation in EFFBR: Vibro Fuel	Test Irradiatons in DFR (Trefoil)
Operation		Max. Linear Rod Power, nominal (W/cm)	600	615	500
		Max. Can Midwall Temp., nominal (°C)	602	602	650
		Max. Can Midwall Temp., hot spot (°C)			
		Max. Internal Gas Pressure (atm)	78	78	<100
		Max. External Pressure (atm)	(low)	(low)	(low)
		Max. Burnup, axially averaged (MWd/t_{Metall})	50 000	50 000	80 000
Fabrication Parameter	External Geometry	External Diameter (mm)	6.35	6.35	6.35
		External Length (mm)	1286	1286	709
	Internal Geometry	Wall Thickness (mm)	0.40	0.40	0.40
		Diametral Gap (μ)	150	-	150
		Upper Axial Blanket Length (mm)	150	150	130
		Fuel Length (mm)	700	700	360
		Lower Axial Blanket Length (mm)	-	-	70
		Fission Gas Plenum Position	Top + Bottom	Top + Bottom	Top
		Length (mm)	188 + 195	188 + 195	130
	Cladding Material		16/13 CrNi	16/13 CrNi	16/13 CrNi
	UO_2-PuO_2-Fuel	Fuel Shape	Pellet	Vibro Powder	Pellet
		Composition (w/o PuO_2)	15	15	20
		Smeared Density (% th.d.)	83	85	83
	UO_2-Blanket, Smeared Density (% th.d.)		83	85	83
	He Filling, initial pressure at room temp. (atm)		1	1	1



Items in Millimeter

F = Fuel
BL = Axial Blanket
PL = Fission Gas Plenum

Fig. 1 PIN GEOMETRY