The Status of Ductile Cast Iron Shipping and Storage Containers in the Federal Republic of Germany

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Papers have been presented in former PATRAM Symposia (e. g. Baatz et al 1980, Keese et al 1980, Droste et al 1983, Anspach et al 1986, Methling et al 1986) describing the development of package designs, results of performance and material testings, applied principles for material evaluations, related quality assurance/compliance assurance (QA/CA) measures and research efforts on shipping and storage containers made from ductile cast iron (DCI).

Since 1979, when the development of DCI-containers began in the FRG, the status has now reached a consolidated level which shall be summarized from the viewpoint of BAM, as the official body in charge of the competent authority to review safety design and the QA/CA measures for transport and storage containers. This view is restricted to Type B approval procedures and does not include any other development or achievement of containers made from DCI. A complementary summary from industry's side is given by Baatz 1989.

Status of Applied Design and Material Acceptance Principles

The principles for the testing and licensing of DCI-container designs are consistent with the IAEA transport regulations and have been presented and published in context by DVM 1987. This reference is the summary of papers on the DCI-subject presented during an international seminar with contributions from the USA, Switzerland, France, Finland, Sweden, Japan, and the FRG.

An updated summary was presented by Günther 1988 in Tokyo during an international symposium on spent fuel storage.

The safety concept applied in the FRG is performance test oriented, using full size samples for the safety demonstration. The characteristics of this method, opposed to conventional fracture mechanic assessments has been highlighted by Wieser 1986. By adequate design of the shock absorbing elements the stress level, in contrary to thinwalled sandwich constructions, is kept below the yield strength under the Type B-accident conditions. This takes the secondary stresses into account as well. Figure 1 summarizes the acceptance criteria. For containers designed for intermediate storage the same concept applies. None of the storage design requirements implicated higher mechanical impacts (Droste et al 1980).

1. *No Fracture of Prototype in IAEA-9 m-Drop Test at -40 °C*

2. *Stress Level* $< 0.5\ R_{p0,2}$

3. *Safety Relevant Material Properties:* $R_{p0,2}$, R_m, A_5, K_{IC}, *Pearlite Content, Graphite Type*

4. *NDE: Minimal Detectable Defect Size Smaller than Flaw Size Corresponding to* $K_I = 50\ MPam^{1/2}$

5. *Specification and Control of All Measures Relevant to Quality of Casting Based on Prototype Fabrication*

Figure 1. Acceptance Criteria for DCI Containers

In this context, BAM performed a multitude of instrumented drop tests using modelled and full-scale prototype casks. In Figure 2 all performance tests with DCI spent fuel casks are summarized:

- 11 9-meter drop tests onto an unyielding target with test objects cooled down to -40 °C,
- 17 9-meter drop tests onto an unyielding target under ambient temperature conditions,
- 3 drop tests from an altitude different to 9 meter onto real targets (not in the frame of Type B test procedures),
- 6 1-meter drop tests on the punch.

Figure 3 shows all drop tests with DCI containers for radioactive waste:

- 7 9-meter drop tests onto an unyielding target in diferent drop positions with test objects cooled down to -40 °C,
- 9 9-meter drop tests onto an unyielding target under ambient temperature conditions,
- 5 1-meter drop tests on a punch.

The test objects had masses from 5 t to 92 t, and a wall thickness from 80 mm to 450 mm. All test objects were instrumented with strain gauges and accelerometers mainly. The test facility meets the IAEA test conditions. The target used had a mass of 1000 t with a 200 mm thick steel plate on top.

Though the decision for the performance test oriented safety concept had serious reasons in the beginning of the development of DCI-containers and to make them competitive against other options for intermediate storage, this decision does not prohibit other safety concepts. In the context of optimized container designs an alternative concept, based upon fracture mechanics is developed at the moment in the FRG which will be applied in parallel to the former one.

Status of Quality and Compliance Assurance Measures

Serial samples as well as the tested prototype are manufactured under extensive quality assurance (QA) programmes, approved by BAM, as the relevant competent authority. These QA measures are combined with compliance assurance (CA) measures. A main difference to anglo/american concepts and a main characteristic of these QA/CA-programmes is the role of independent experts acting on behalf of the competent authority, whose main task is to inspect real items (components) resp. its properties rather than to audit the QA-systems (Wieser and Rödel 1983). In order to economize the QA/CA efforts a grading system applies (Figure 4).

DESIGN CASTOR Ia

1/2 SCALED MODEL
MASS 8 t

9 m DROP TEST ON UNYIELDING TARGET

LID CORNER	-40° C	WITH SHOCKABSORBER	
BOTTOM	-40° C	WITHOUT	"
TRUNNIONS	-40° C	WITHOUT	"
LID CORNER	-40° C	WITH	"
LID CORNER	-40° C	WITHOUT	"
BOTTOM	-40° C	WITH	"

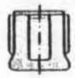
FIRE TESTS (OPEN OILFIRE)
2x WITH SHOCKABSORBERS
1x WITHOUT "

PROTOTYPE
MASS 80 t

9 m DROP TEST ON UNYIELDING TARGET

BOTTOM	RT	WITH SHOCKABSORBER	
LID CORNER	RT	WITH	"
TRUNNIONS	-40°C	WITHOUT	"
TRUNNIONS	RT	WITHOUT	"

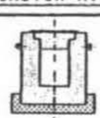
FIRE TEST (OPEN OILFIRE)
1x WITHOUT SHOCKABSORBERS



BOTTOM SECTION
MASS 18 t

FIRE TEST (OPEN OILFIRE)
1x WITHOUT SHOCKABSORBER

DESIGN CASTOR-MTR

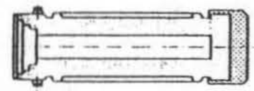


SERIAL SAMPLE 05
SERIAL SAMPLE US
MASS 11 t

9 m DROP ON UNYIELDING TARGET
SIDE ON -40° C WITH SHOCKABSORBER
(WITH ARTIFICIAL FLAW MID OF LENGTH)

9 m DROP ON UNYIELDING TARGET
BOTTOM CORNER RT WITH SHOCKABSORBER

DESIGN CASTOR Ic



SERIAL SAMPLE 03
MASS 80 t

19,5 m DROP TEST ON REAL TARGET
SIDE ON RT WITHOUT SHOCKABSORBER

15 m DROP TEST ON POWERPLANT SHOCKABSORBER
BOTTOMCORNER RT WITHOUT SHOCKABSORBER

9 m DROP TEST ON UNYIELDING TARGET

TRUNNIONS	RT	WITHOUT SHOCKABSORBER	
BOTTOM/30° INCL.	RT	WITHOUT	"
TRUNNIONS	-40° C	WITHOUT	"

1 m DROP ON PUNCH
LID CENTRE RT WITH SHOCKABSORBER
PRESSURE GAGE
IN LID RT WITH SHOCKABSORBER

DESIGN CASTOR IIa

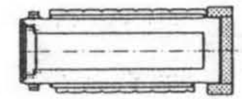
1/2 SCALED MODEL
MASS 14 t

9 m DROP TEST ON UNYIELDIENG TARGET

LID CORNER	RT	WITH SHOCKABSORBER	
BOTTOM	RT	WITH	"
TRUNNIONS	RT	WITHOUT	"
LID CORNER	RT	WITH	"
TRUNNIONS	RT	WITHOUT	"
LID CORNER	RT	WITH	"

1 m DROP ON PUNCH
LID CENTRE RT WITH SHOCKABSORBER
LID CENTRE RT WITH "

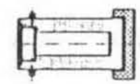
DESIGN TN 900



SERIAL SAMPLE 03
MASS 80 t

9 m DROP TEST ON UNYIELDING TARGET
SIDE ON/TRUNNIONS -40° C
WITHOUT SHOCKABSORBERS

DESIGN TN-THTR



PROTOTYPE
MASS 27 t

9 m DROP TEST ON UNYIELDING TARGET

SIDE ON	-40° C	WITH SHOCKABSORBERS	
BOTTOM	RT	WITH	"
LID CORNER	RT	WITH	"

3,5 m DROP TEST ON REAL TARGET
BOTTOM RT WITHOUT SHOCKABSORBERS

1 m DROP TEST ON PUNCH
LID CENTRE RT WITH SHOCKABSORBERS

DESIGN TN 1300

1/3 MODEL
MASS 4 t

9 m DROP TEST ON UNYIELDING TARGET

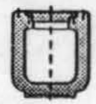
BOTTOM 2x	RT	WITH SHOCKABSORBERS	
LID CORNER	RT	WITH	"
SIDE ON/ TRUNNIONS	RT	WITHOUT SHOCKABSORBERS	

1 m DROP TEST ON PUNCH
LID CENTRE RT WITH SHOCKABSORBERS

FIRE TEST (OPEN OILFIRE)
1x WITH SHOCKABSORBERS

Figure 2. Type B-Performance Tests with Spent Fuel Containers

Design MOSAIK I



Prototype
Serial sample 01
Mass 5,3 t

9 m drop tests on unyielding target

bottom	-40° C	without shockabsorbers
lid corner	-40° C	" "
side on	-40° C	" "

fire test (open oilfire)
without shockabsorbers

Design MOSAIK II KfK

Serial sample 77
Mass 6,5 t

9 m drop test on unyielding target

side on	-40° C	without shockabsorbers

Design MOSAIK III-12

Serial sample 58
Mass 4,3 t

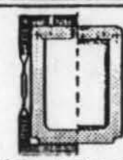
9 m drop tests on unyielding target

side on	RT	without shockabsorbers
side on	-40° C	" "

1 m drop test on punch

lid centre	RT	wihtout shockabsorbers

Design MOSAIK II-15



Serial Sample 91
Serial Sample 96
Mass 7,2 t

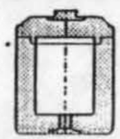
9 m drop tests on unyielding target

bottom	RT	with shockabsorbers
lid corner	RT	" "
side on	RT	" "
side on	RT	without shockabsorbers

1 m drop test on punch

lid centre	RT	without shockabsorbers

Design MOSAIK CLAB



Prototype
Mass 7 t

9 m drop tests on unyielding target

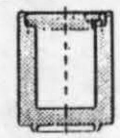
bottom 2 x	RT	without shockabsorbers

9 m drop test on concrete plate

bottom	RT	without shockabsorbers

1 m dropt test on punch
bottom centre - sm. lid 2 x
RT without shockabsorbers

Design TN-SAB / G300



Prototype
Mass 8 t

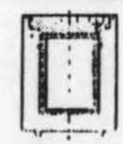
9 m drop tests on unyielding target

bottom	RT	without shockabsorbers
side on	-40° C	" "
lid corner	RT	" "

1 m drop test on punch
lid-drainhole plug
RT without shockabsorbers

firetest (open oilfire)
without shockabsorbers

Design TN-SAB / G300 Pb



Prototype
Mass 10 t

9 m drop tests on unyielding target

bottom	RT	without shockabsorbers
lid corner	RT	" "
side on	-40° C	" "

1 m drop test on punch
lid - drainhole plug
RT without shockabsorbers

Figure 3. Type B-Performance Tests with Waste Containers

Grades	Object	Consequences
Class 1	Components or Properties Directly Assuring - Leaktightness - Nuclear Safety	Testing, Inspection Certification by - Manufacturer - Works Expert - Independent Expert
Class 2	Components or Properties Directly Assuring - Shielding Indirectly Assuring - Leaktightness - Nuclear Safety	Testing, Inspection, Certification by - Manufacturer - Works Expert
Class 3	All Other Items or Properties	Compliance Measures as Agreed

Figure 4. Compliance Assurance Measures - Grading System

The cask body as a relevant component of the leaktight system drops under Grade 1, for which the independent inspection is required. The CA-programme with respect to the control of material properties is aimed to comply the individual data of any manufactured serial sample with the ones of the approved material data sheets. This shall be achieved by using material specimens taken out of the wall of the cast pieces. It is important in this context that the values used for quality control purposes have been selected because they

- characterize resp. identify sufficiently the material quality based upon the prototype data and
- they are possible to be tested during the manufacturing controls, having the material sampling technique and the sample sizes in mind.

The values of the material data sheets, therefore, are not necessarily suited for any safety assessment. Figure 5 shows the set of values to be complied with. The figures therein are to be looked as a minimum. According to the achieved level of properties these figures are adapted relevant to the design (cast modulus) and casting method.

- Material Properties of Nodular Cast Iron Identified as Relevant for Safety: $R_{p0,2}$, R_m, A_5, K_{IC}, Pearlite Content, Graphite Type
- Material Properties to be Specified Corresponding to Modulus and Casting Method
- Sampling out of Wall
- Minimum/Maximum Figures to be Met

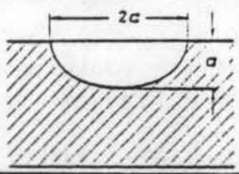
$R_{p0,2}$	$\geq$ 180 MPa	
R_m	$\geq$ 250 MPa	
A_5	$\geq$ 6 %, Minimum Valid Single Value	
Pearlite Content	$\leq$ 20 %	
Graphite Type:	no Chunky Graphite	

- No Specified Fracture Toughness if All Other Material Specifications Are Met and K_{IC} Is Supposed To Be 50 $MPam^{1/2}$

Figure 5. DCI - Material Specifications for QA/CA Purposes

Main results of materials investigations, both from prototypes and serial samples, achieved material data (strength, ductility, fracture toughness, metallography), correlations and the result of a literature survey is part of a paper by R. Helms and J. Ziebs in DVM 1987.

A sensitive point of the CA measures besides the materials testing is the ultrasonic investigation. The sensitivity and the thresholds of these US-testings are justified by a fracture mechanics appraisal using lower bound figures for the fracture toughness of DCI and the basic philosophy, that the combination of (Type B) accident loads and undetected, unacceptable defects is not subject of the safety assessment (probabilistic cut-off). A comparison of these K_{IC}-figures, stress concentrations and limits for US-indications is given in <u>Figure 6</u>. The figures therein apply for thickwalled spent fuel containers. For the thinner waste-containers even smaller thresholds for the US-testings have been set forth.

ASME-Calculation Section IX, A-3200-1		
Assumed Defect Maximum Accident Stress (Type B-Level) σ_b = 120 MPa	Surface Flaw, Perpendicular to Main Stress  	
Lower Bound K_{IC} - Value	47 $MPam^{1/2}$ (1500 $Nmm^{-3/2}$)	63 $MPam^{1/2}$ (2000 $Nmm^{-3/2}$)
Flaw Size for	a	a
a/2c = 0.1	44 mm	74 mm
a/2c = 0.25	65 mm	116 mm
Flaw Areas for		
a/2c = 0.1	152 cm^2	430 cm^2
a/2c = 0.25	133 cm^2	423 cm^2

Ultrasonic Test Procedure - Acceptance Criterias		
Orientation/Location of Indications		
Parallel to Surface	Perpendicular to Surface	Sealing and Service Loaded Areas
No Single Reflector > 50 cm^2		No Indications Above Recording Threshold (10 mm FBH)
No Reflectors With a Total Area > 250 cm^2/m^2		
No Backwalldrop > 20 dB		
	No Indications >10% of Wall Thickness	

Figure 6. DCI-Containers, Correlation of Brittle Fracture Assessment and Acceptance Criteria for US-Testing

The test specifications for ultrasonic testing, approved by BAM specify:

- field of application, purpose and time of test
- qualification of testing staff
- areas to be tested and surface finish
- testing equipment and test method
- documentation and evaluation of signals.

Testing is performed with a pulse-echo reflection mode and a through transmission technique. The orientation of sound beams and the methods are to be chosen in such a way that each volume element is covered by a reflection and by a through transmission mode. The sensitivity of the testing equipment was adapted to the special case of thick-wall castings taking into consideration the workmanship-quality level of the castings and corresponding inclusion-sizes in terms of their ultrasonic response.

The following recording levels have been specified:

1. echo signals corresponding to a flat-bottom hole of 10 mm diameter shall be documented
2. backwall echo signals with an echo height deviating by more than 20 dB from the average shall be documented

3. echo height drop of greater than 20 dB at through transmission mode has to be documented
4. for information, the sound velocity shall be measured in various directions.

For this kind of signals further ultrasonic tests are required to accuratly determine the nature and size of defects.

Background, test techniques, sensitivities, calibration and effectivity of the applied nondestructive testings, in particular of the ultrasonic investigation of DCI shipping containers, is highlighted in the paper of H. Wüstenberg et al in DVM 1987.

Status of Research Efforts

Though this safety concept and acceptance criteria have now been accepted since years, research work is performed in order to establish an even broader and more reliable basis for the safety analyses demonstration, in particular in view of optimized designs and the use of alternative safety concepts (classic fracture mechanics). The status of these efforts, performed by BAM, is presented in BAM 1989 and Günther 1989.

Status of Applications, Licenses, Experiences

The status of applications under the transport legislation is given by the following tables, in which for any of the design types data on the total mass, applied/licensed contents, the progress in the licensing procedure, granted approvals, revalidations in second countries, number of manufactured samples and experiences are summarized. An endorsement in these lists required the submittal of the official application under the transport legislation completed by the safety analyses report, unless otherwise indicated. 'Certification in progress' means that the result of BAM's official judgement on the mechanical/thermal design and the QA/CA measures as a presupposition of the certificate of approval issued by the PTB (Physikalisch-Technische Bundesanstalt) has been completed or almost completed. In case of a foreseable positive result of the design review by BAM, a letter of intent ('LOI') is granted on request. For some designs, samples have already manufactured prior to the completion of the approval procedure. Though this sequence has some advantages with respect to an early experience with the QA/CA-system and consequent improvements, it is under the full risk of the applicant and may lead to the rejection of samples.

Table 1 - Spent PWR and BWR Fuel Containers

14 designs have been applied for approval, 9 of them have already been approved, 2 approvals have been revalidated abroad. One design has been licensed in the USA for the storage of spent fuel. All these containers are designed for dual transport/storage purposes. For the use as 'pure' shipping containers, two designs have additionally been qualified in a simplified version (replacement of metallic gaskets by elastomer-0-rings). In total, 49 samples have already been manufactured and partly gained experience in shipments and storage actions.

Table 2 - Spent Research Fuel Containers

This table also includes containers for spent fast breeder elements (Super Phenix, France and BN 600/800, USSR). 3 of the 6 applied designs have been approved and revalidated in second countries. 9 casks have been manufactured.

Table 3 - Containers for Spent Fuel from High Temperature Gas Cooled Reactors

For the shipment and intermediate of spent fuel (graphite ball type) from the research reactors in Jülich and the 300 MW pilot plant in Hamm-Uentrop, 3 designs have been applied, 2 of them approved and 5 samples already manufactured. Because of the fact that there are no reprocessing plans for that type of fuel, a larger number of samples is expected to be built in the near future.

Table 1 — OCI-shipping container designs for spent PWR/BWR fuel
Approval procedures under the transport legislation — May '89

Design	Total mass t	Contents	Cool. time years	Burnup MWd/t	Certific. in progress	Approved	Revalid. abroad	Sample(s) manufactured	Experiences/ Shipments
CASTOR Ia	85	4 PWR-FE	1 1,5	35.000 45.000				1	Shipm./stor. Biblis
CASTOR KRB-MOX	63	16 MOX-FE	5	14.000			Sweden	4	Shipm. CLAB, Sweden
CASTOR IIa	131	9 PWR-FE	1 1,5	35.000 45.000					
CASTOR Ib	64	4 PWR-FE	0,8 0,8	35.000 37.000				7	Shipments Stade
CASTOR Ic	85	16 BWR-FE	1 1	26.840 27.000				9	Storage in Würgassen
CASTOR Ic/21	88	21 BWR-FE MOX-FE	1,75 2,5	45.000 45.000					
TN 1300/1-12	120	12 PWR-FE	2,5	42.000				2	Shipments Biblis
TN 900/1-21	81	21 BWR-FE	1,3	35.000				7	Cold handling
CASTOR TVO	102	41 BWR-FE	5	45.000			Finland	1	Storage in TVO Finld.
CASTOR WWER 1000	110	21 PWR-FE	2 3	28.000 40.000	LOI			1	Handling in WWER Woronesh, USSR
CASTOR IIb	85	8 PWR-FE	0,74	42.000				3	Sched. 12 shipments
CASTOR V/21	115	21 PWR-FE	5	35.000			(Storage License, USA)	13	Storage in TVA, USA
CASTOR S1	90	6 PWR-FE	1,25	45.000				1	Cold handling in Sellafield, UK
CASTOR S2	85	17 BWR-FE	1 1,25	35.000 45.000					

Table 2 — OCI-shipping container designs for spent research fuel
Approval procedures under the transport legislation — May '89

Design	Total mass t	Contents	Cool. time years	Burnup MWD/t	Certific. in progress	Approved	Revalid. abroad	Sample(s) manufactured	Experiences/ Shipments
CASTOR Ic Diorit	79	350 MTR-FE						1	Storage in EIR, Ch
CASTOR MTR	11	15 MTR-FE DIDO 16 MTR-FE MERLIN					S,B,CND, NL, F	6	
CASTOR MTR-F	13	" " Waste						2	Sched. 12 Shipments
CASTOR SPX-T	110	7 BREEDER FE SPX	2	125 000			F		
CASTOR K12	105	12 " " 9 " "	5 3	125 000 125 000					
CASTOR BN	120	36 BREEDER FE BN	1	125 000					

Table 3 — OCI-shipping container designs for spent HTGR fuel
Approval procedures under the transport legislation — May '89

Design	Total mass t	Contents	Certific. in progress	Approved	Revalid. abroad	Sample(s) manufactured	Experiences/ Shipments
CASTOR THTR-AVR	28	2100 HTGR FE 1900 AVR FE				1	Cold handling
CASTOR AVR-T	19	1900 AVR FE				1	
TN-THTR 1/IId	30	2100 HTGR FE				3	Cold handling

Table 4 - Waste Containers

the largest numbers of DCI-containers have been manufactured for the shipping and storage of waste, actually more than 2000. The contents is specified as nonconsolidated scrap, concentrates, resins etc. Some of the designs include additional internal lead shieldings in different thickness. The DCI-wall thickness ranges from 80 mm to 220 mm, the total mass from 3 till 20 tons. The shape is either a cylindrical or prismatic and covers the design requirements for final storage in the KONRAD-repository (PTB 1986). For transport purposes, they are equipped with shock-absorbers.

13 designs (most of them in additional modifications) have been applied for approval, two of them approved. Most of the manufactured samples are actually used for intermediate storage of waste in nuclear power plants and installations and will be shipped as soon as the final repository KONRAD will be taken into service.

Table 4 — DCI-shipping container designs for Waste — Approval procedures under the transport legislation — May '89

Design	Total mass t	Contents	Certific. in progress	Approved	Revalid. abroad	Sample(s) manufactured	Experiences/ Shipments
MOSAIK I	6	Waste				90	Storage in nuclear installations
MOSAIK II KfK	7	"	LOI			400	"
MOSAIK III	3 - 5	"				325	"
MOSAIK II-15	8	"				1075	"
MOSAIK CLAB	8	"		Appr. in Sweden		15	Storage in CLAB, Sweden
TN-SAB/G300 Pb	9	"				80	Storage in nuclear installations
TN-SAB/G300	7	"				20	"
TN-SAB/G500	6	"				5	"
TN-SAB/G800	5	"				55	"
TN ROBE-Cont.	15	"				11	"
TN-SAB/G650 PbV	6	"				90	"
MOSAIK MIC	9	"				1	
WACO II	20	"				12	

Table 5 - Highactive Waste Containers

This list is a sum of flask designs for different highactive liquid and vitrified waste reprocessing, except one which is designed for activated absorber elements from the fast Super Phenix breeder, 2 designs. 9 samples of flasks for the shipment and intermediate storage of HAW-glas canisters are ready to be used.

Table 6 - Container for Direct Final Storage of Spent Fuel

In the frame of a research program on alternative "Entsorgungs"-techniques, a DCI-container design for the direct final storage of spent fuel was developped and one sample manufactured. In case of a positive decision, it would have to cope also with the transport regulations. This design (see Einfeld and Popp, 1986) was designed to contain 8 PWR-fuel elements, cut and bundled.

Table 5 — DCI-shipping container designs for highactive waste. Approval procedures under the transport legislation — May '89

Design	Total mass t	Contents	Certific. in progress	Approved	Revalid. abroad	Sample(s) manufactured	Experiences/ Shipments
CASTOR Barre	101	12 Abs.Elem.	▒▒▒				
CASTOR IIa HAWC	121	800 1 HAWC	▒▒▒				
CASTOR V HAWC	80	2000 1 HAWC	▒▒▒				
CASTOR GSF	22	5 HAW-Canisters	▒▒▒			8	
CASTOR 21 HAW	116	21 HAW-Canisters				1	

Table 6 — DCI-shipping container designs for final storage of spent PWR/BWR fuel — May '89

Design	Total mass t	Contents	Certific. in progress	Approved	Revalid. abroad	Sample(s) manufactured	Experiences/ Shipments
POLLUX	65	8 PWR-FE (cut and bundled)		Research/ Development		1	

Summarizing all main data of these tables in May 1989, 41 Type B package designs are in the certification process, 15 approvals have already been issued and 2162 samples been built. Six designs have been revalidated or approved resp. licensed abroad.

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