30th NENE 2021
September 6 - 9
BLED-SLOVENIA
International Conference Nuclear Energy for New Europe

Decommissioning of Activated Fragments of the Jaslovské Bohunice V1 NPP VVER-440 Pressure Vessel

Štefan Čerba, Milan Myslík, Branislav Vrban, Jakub Lüley, Vladimír Nečas
Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and
Information Technology, Institute of Nuclear and Physical Engineering
Ilkovičova 3
812 19, Bratislava, Slovakia
stefan.cerba@stuba.sk, myslikmilan@gmail.com, branislav.vrban@stuba.sk,
jakub.luley@stuba.sk, vladimir.necas@stuba.sk

ABSTRACT

With the construction of new nuclear power sources, the issue of decommissioning of nuclear power plants has also come to the fore for a considerable time. During the decommissioning of a nuclear power plant, decisions need to be made that are often influenced by the specific decommissioning facility. The decommissioning of the V1 NPP in Slovak Republic has arrived into the phase of fragmentation of the reactor pressure vessel and storage of resulting fragments. For this purpose, it is always necessary to perform analyses dealing with storage options. This paper is dealing with the possibilities of the decommissioning of these components. The first part is focused on the categorization of reactor pressure vessel fragments, based on various criteria. In the next part, analyses aiming on the possibilities of fragments storage are presented. After determining the initial conditions, the main part of the work deals with the estimation of dose rates in the vicinity of fibre-reinforced concrete containers and storage conditions in the Integral RAW Storage Facility using the SCALE6 code system. As the most important result of the work, the number and type of fibre-reinforced concrete containers are presented, which are necessary for storing the entire reactor pressure vessel while respecting the postulated limits.

1 INTRODUCTION

The peaceful use of nuclear energy in Slovakia started in 1958 by building the A1 nuclear power plant (NPP) in Jaslovské Bohunice. It was an NPP with the Czechoslovak KS-150 nuclear reactor, which was designed to use natural uranium as fuel, heavy water as moderator and CO_2 as coolant. The NPP was commissioned in 1972, but after two relatively serious accidents (INES 3 and 4) in 1976 and 1977, it had to be shut down. At the same period, the construction of two Russian type VVER-440-V230 units was started, also in Jaslovské Bohunice. These light water cooled, low enriched UO_2 fueled reactors were put into operation in 1978 and 1980. Later on, 2+2 additional, but modernized VVER-440-V213 units were built at the same site and also in Mochovce, where the construction of the 3 & 4 units is currently being finalized. Due to the older V-230 design and the related service life, the first two units of the Jaslovské Bohunice NPP, called the V1 NPP, were after almost 30 years of successful operation shut down in 2006 and 2008. These units are currently decommissioned, with the expected end in 2025 [1]. The decommissioning timeline is shown in Figure 1.

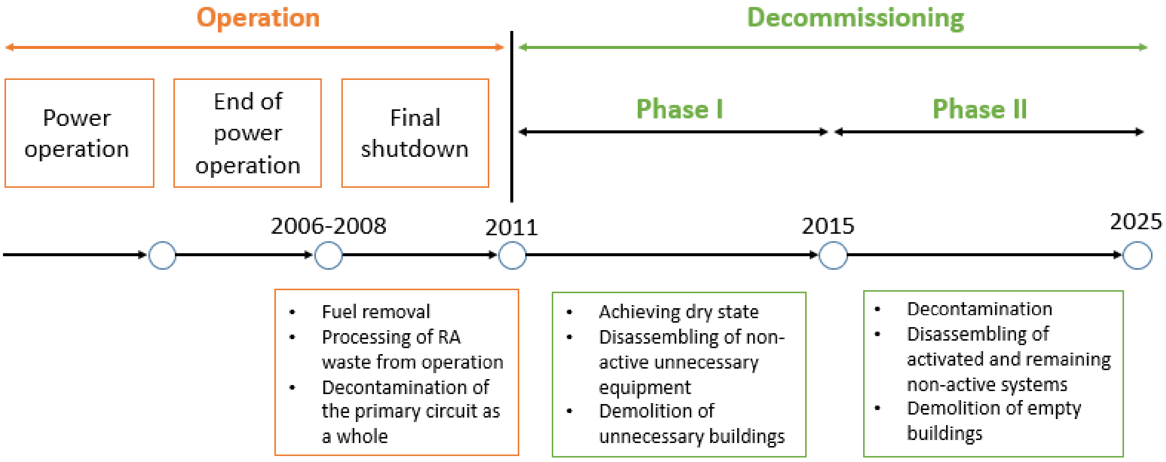


Figure 1: Decommissioning time plan [2]

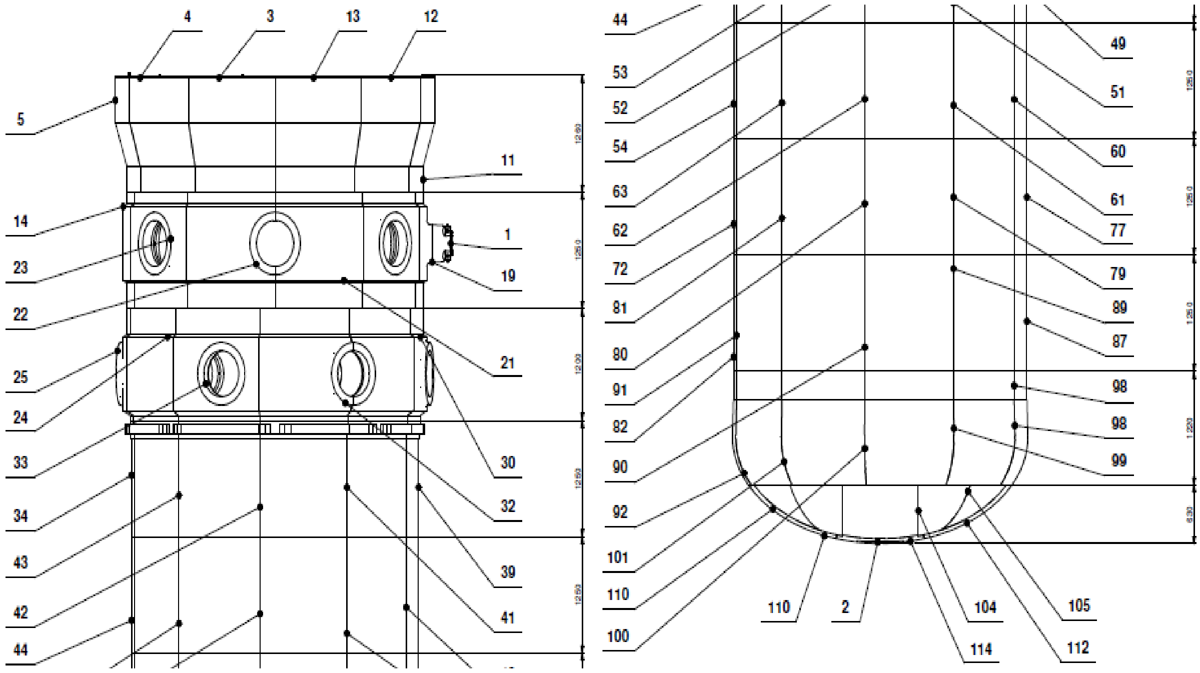
The decommissioning process was planned for two phases. The current second phases consist of mainly decontamination and disassembling of activated parts, among which the demounting, removal and storage of the reactor pressure vessel (RPV) represents one of the most complicated tasks. Based on the feasibility study conducted by Javys a.s. [3], 7 scenarios were designed for the decommissioning of the RPV of the V1 NPP. The brief summary of these scenarios can be found in Table 1. After a multi-criteria analysis, these 7 scenarios were reduced to RPV 1-b and RPV 1-c, further divided to variants A1, A2 and A3. Among these variants, A3 was selected as the final scenario. This scenario consists of three steps:

1. Primary fragmentation of the large RPV ring
2. Secondary fragmentation
3. Storage of fragments in fiber-reinforced concrete containers (FCC)

Table 1: Scenarios of the RPV decommissioning [3]

Scenario	Description	Decision
RPV 1-a	Long-term storage of RPV as a whole	Not feasible – no capacities available
RPV 1-b	Temporary storage of RPV as a whole	Feasible – Variant A1
		Feasible – Variant A2
RPV 1-c	Disassembling of RPV as a whole with subsequent fragmentation	Feasible – Variant A3
RPV 1-d	Disassembling of RPV as a whole with subsequent fragmentation for remelting	Not feasible – remelting is not sufficient
RPV 2	Disassembling of RPV to large sized components	Not feasible – economic reasons
RPV 3-a	Disassembling of RPV to small sized components	Not feasible – economic reasons
RPV 3-b	Disassembling of RPV to small sized components for remelting	Not feasible – remelting is not sufficient

According to this scenario, the primary and secondary fragmentation of a single RPV from one reactor unit would lead to 184 fragments. In order to optimize the whole process and to minimize the number of FCCs the number of fragments could be reduced to 114. The fragmentation plan is shown in Figure 2.



a; top part b; bottom part

Figure 2: Fragmentation plan of the RPV [1]

It is foreseen that the fragmentation of the RPV will result in low, intermediate and high level waste, among which the majority would be intermediate level waste, which could be according to the legislation of Slovak republic stored in fiber-reinforced concrete containers. For these containers the following requirements should be met:

1. The dose rate at the outer surface of the transport package (FCC + shielding) shell not exceed 2 mSv/h during transport
2. The dose rate at the distance of 2 m from the transport package shell not exceed 0.1 mSv/h during transport
3. The dose rate at the outer surface of the transport package shell not exceed 10 mSv/h at the Integral RAW storage facility

In case that the original “VBK0” design of the FCC containers could not meet the listed requirements, also special “VBK2”, “VBK4” or “VBK10” containers, equipped with 2,4 or 10 cm of lead shielding, can be used. It should be noted, that FCC containers are in general designed for low level radioactive waste, but using cementation, also components of intermediate level waste can be distributed in the mixture, as long as the above mention limits for transportation and storage are met.

2 CATEGORIZATION OF RPV FRAGMENTS

In order to distribute the RPV fragments to basic or shielded FCC containers, while meeting the transportation and storage limits, and to minimize the number of used containers, the RPV fragments should be categorized based on their shape, weight and radioactivity.

2.1 Categorization based on shape

Based on their shape, the 114 fragments resulting from the fragmentation plane can be categorized as shown in Table 2.

Table 2: RPV categories based on shape

Type	**Description**	**Height of fragment [cm]**	**Number of fragments**
S1	RPV flange	126	11
S2	RPV nozzles	120 – 125	20
S3	Region between the bottom and nozzles	122 – 125	68
S4	RPV bottom	63	13
Unclassified	Other	Other	2

2.2 Categorization based on weight

The range of the weights of the 114 RPV fragments is between 46 and 3 547 kg, while the maximal load of a single FCC container is 10 780 kg. Taking this limitations into account, the categories shown in Table 3 were selected.

Table 3: RPV categories based on shape

Type	**Weight range [kg]**	**Number of fragments**
W1	< 1000	18
W2	1000 – 2000	65
W3	2000 – 3000	20
W4	> 3000	11
Total	N/A	114

2.3 Categorization based on activity

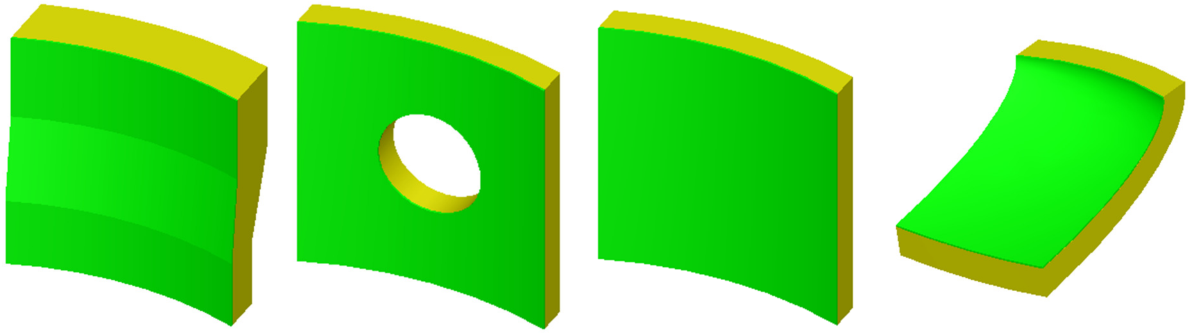
Based on the radioactivity of each fragment, five categories were selected, while each category represents a level of radioactivity higher by the previous one, exactly by an order of magnitude. The categories are shown in Table 4.

Table 4: RPV categories based radioactivity

Category	**A1**	**A2**	**A3**	**A4**	**A5**	**Total**
Activity [Bq]	1E+8	1E+9	1E+10	1E+11	1E+12	-
Number of fragments	1	55	28	0	30	114

2.4 Selection of representative fragments

Based on the intersection of all three categories, all RPV fragments were categorized. In order to ease the simulations and their storage management, among all 114 fragments 4 representative fragments were selected and the calculation models were created only for these fragments. It is foreseen that the results of the representative fragments can be used for all members of the group, for which the representative segment was selected. These fragments are shown in Figure 3.



a; Type 1 b; Type 2 c; Type 3 d; Type 4

Figure 3: Fragmentation plan of the RPV

The representative fragments are the following ones:

- Type 1 – Shape S1, weight W4, Activity A2 – max 2 fragments per FCC
- Type 2 – Shape S2, weight W3, Activity A2 – max 3 fragments per FCC
- Type 3 – Shape S3, weight W2, Activity A5 – max 4 fragments per FCC
- Type 4 – Shape S4, weight W2, Activity A2 – max 2 fragments per FCC

3 CALCULATION METHODOLOGY AND CASES

3.1 SCALE6 system

All calculations presented in this paper were performed using the SCALE6 [4] system, especially the MAVERIC sequence and the Monaco Monte Carlo radiation transport code. For each calculation case and representative segment, a standalone calculation was performed, using multi-group approach with v7.0-27n19g XS library, processed based on ENDF/B-VII.0 [5] evaluated data in 27 neutron and 19 gamma groups. The calculations were performed in forward mode, without using variance reduction techniques. The required statistical uncertainty was achieved by using a total number of 5E9 histories. The time required for a single calculation was between 48 – 72 h. The results of the calculations were evaluated using meshtalies and point detectors located, in accordance with the transportation and storage limits, on the FCC surface and 2 m from the surface. The calculation cases were compared based on the neutron and gamma fluxes as well as effective doses based on the ICRU-57 conversion factors implemented directly in SCALE.

3.2 Calculation cases

Using the representative fragments selected in the previous chapter, the following cases of analyses were performed:

- Source effect analysis
    - Type 3 fragments, 1 in a single FCC
    - Activity of the fragment defined as effective Co-60 equivalent
        - Defined separately for base material (14 cm) and the weld (1 cm)
        - Common source for both materials (15 cm)
- Shape effect analysis
    - Type 3 fragments, 4 in a single FCC
    - 3 geometry configurations to evaluate geometry self-shielding
        - G1 – All in a row (Figure 4a)
        - G2 – high activity surfaces facing each other (Figure 4b)
        - G3 – high activity surfaces back to each other (Figure 4c)

- Design of shielding for fragments beyond the radiation limits
    - Type 3 fragments, 2 in a single FCC
    - Finding a shielding thickness (Pb or Fe) to ensure effective doses below 10 mSv/h on the surface of the FCC (transportation limit)
    - Calculation based on the attenuation of gamma radiation based on Eq.(1), where φ_0 and φ_x represent the gamma fluxes inside and outside the shielding layer
- Summary of FFCs
    - Summary of types and categories of fragments as well as number of FCCs
    - Comparison with real data from the decommissioning implementation plan

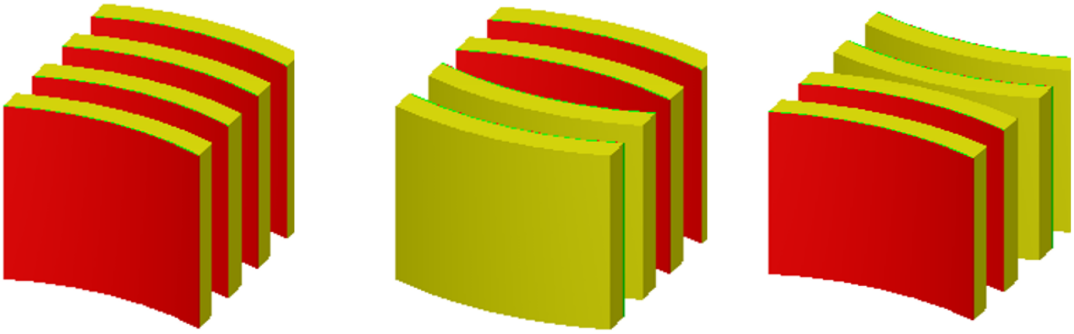

a; G1 b; G2 c; G3

Figure 4: Evaluated geometry configurations

$$x = -\frac{ln\left(\frac{\varphi_x}{\varphi_0}\right)}{\mu} \tag{1}$$

4 RESULTS AND DISCUSSION

The results of the source effect analysis are shown in Table 5. The table presents the effective doses of gamma radiation at the outer side, front and top surface of the investigated FCC as well as the relative deviation *Δ* from the case with separately defined sources. The uncertainty represents the combined standard uncertainty from the calculations. As it can be seen, the case with separate sources provided lower effective doses in 2 out of 3 directions, this case was selected as the most conservative one and is used for further analyses.

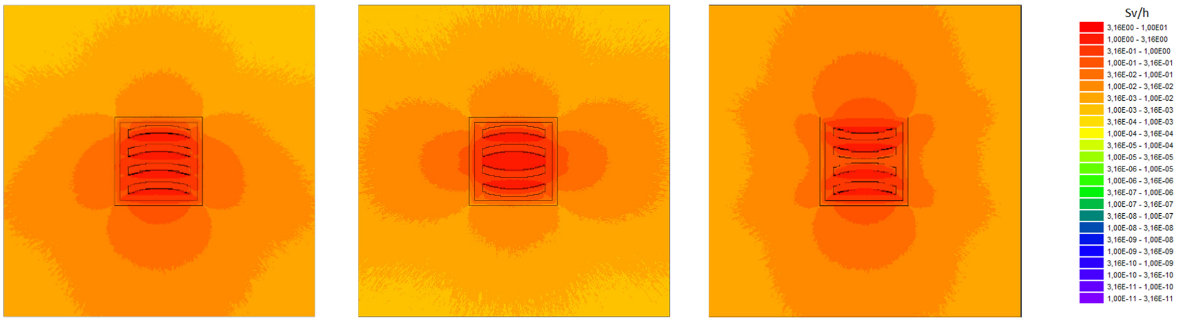
Table 5: Results of the source effect analysis

Definition of the source	**Effective dose of gamma radiation [mSv/h]**		
	Side	**Front**	**Top**
Separate sources	58.7 ± 1.6	16.2 ± 0.9	47.6 ± 1.4
Common source	61.1 ± 1.9	15.9 ± 1.0	47.7 ± 1.6
Δ [%]	-4.1 ± 0.1	1.9 ± 0.1	-0.2 ± 0.1

The results of the shape effect analysis are shown in Table 6 and the top views of gamma dose rates per various geometry configurations can be seen in Figure 5. In this analysis the “G1” geometry was used as the reference one. The dose rates were calculated at the side, front and top walls of the FCC. The comparison of effective doses is showing different behaviour in each direction. While the “G3” seemed to be the most promising one in the side and top view, in the front view, it provided the worst properties. Taking into account all directions, the “G1” configuration was selected as the most promising one, due to the more uniform distribution of gamma dose rates in each direction, which could ease the design of shielding if necessary.

Table 6: Results of the shape effect analysis

Definition of the source	Effective dose of gamma radiation [mSv/h]		
	Side	Front	Top
G1	41.8 ± 0.8	15.8 ± 0.5	30.8 ± 1.0
G2	58.7 ± 1.7	16.2 ± 0.9	47.6 ± 1.4
G3	22.7 ± 0.8	84.2 ± 1.7	16.6 ± 0.7
ΔG2/G1 [%]	40.4 ± 4.8	2.5 ± 6.5	54.6 ± 6.7
ΔG3/G1 [%]	-45.7 ± 2.1	432.9 ± 4.5	-46.1 ± 2.7



a; G1 b; G2 c; G3 Scale

Figure 5: Top view of the gamma dose rates per various geometry configurations

The 1D approach based on gamma flux attenuation identified that 10 mSv/h transportation limit can be met by using 6.91 cm thick steel or 4.36 cm thick lead shielding. In the next step a detailed 3D analysis was performed investigating 5 cm lead and 7 cm and 8 cm steel shielding. The results are shown in Table 7. They are showing, that all three investigated materials and thicknesses could possible meet the 10 mSv/h requirement, however taking into account the statistical uncertainty of the calculation and also economic reasons, the 8 cm Fe shielding was selected as the most promising candidate for shielding.

Table 7: Results of the shielding analysis

Shielding type	Effective dose of gamma radiation [mSv/h]		
	Side	Front	Top
No shielding	41.8 ± 0.8	15.8 ± 0.5	30.8 ± 1.0
Pb – 5 cm	4.1 ± 0.3	0.8 ± 0.1	3.4 ± 0.3
Fe – 7 cm	9.5 ± 0.4	1.8 ± 0.5	7.9 ± 0.4
Fe – 8 cm	6.7 ± 0.3	1.4 ± 0.2	5.5 ± 0.3

Based on the classification presented in previous chapters, all 114 fragments were distributed in basic and shielded fibre-reinforced concrete containers. The summary of containers is presented in Table 8. The results are showing that it is required to use 21 basic and 8 Fe shielded FCC containers to store all 114 fragments. Compared to the implementation plan [3], which required 23 basic and 8 shielded FCC, we managed to reduce the number of containers and to achieve better economic indicators, while meeting the required transport and storage limits. The differences could be caused by different assumptions made in the implementation plan and also a more conservative approach compared to the SCALE multi-group approach.

Table 8: Summary of FCC containers

Fragment type	**Number of fragments**	**Basic FCCs**	**Shielded FCCs**
S1	11	6	0
S2	20	7	0
S3	68	8	8
S4+other	13+2	2+1	0
Total	114	**21**	**8**
Implementation plan	114	**23**	**8**

5 CONCLUSION

The decommissioning of the V1 NPP in Slovak Republic has arrived into the phase of fragmentation of the reactor pressure vessel (RPV) and storage of resulting fragments. For this purpose, it is always necessary to perform analyses dealing with storage options of RPV fragments. Based on the implementation plan of the decommissioning the Jaslovské Bohunice NPP V1 reactor pressure vessels will be fragmented to 114 pieces per unit, which will be subsequently stored in fiber-reinforced concrete (FCC) containers. These containers could be however used only, if they meet the radiation limits for transportation and storage. In order to ease the management of the storage of RPV fragments, first a categorization had to be made based on the shape, weight and activity of the fragments. Since the RPV steel consists of the base material and the weld, an analysis was performed to find out, that it is the most conservative to model the source of induced activity separately in these two materials. The next analysis, aimed on self-shielding, pointed out, that the most effective way of placing the RPV fragments in the FCCs is to put them all in a row. Only this configuration can ensure uniform distribution of the dose rates. Even though the majority of RPV fragments can be categorized as a low or intermediate level waste, but in case of several FCCs the transportation limits are difficult to meet using basic FCCs. For these containers a special design was developed, that consists of an 8 cm Fe layer. The most important finding of this paper is the estimate of the number of containers for storage, which represents 21 basic and 8 shielded fiber-reinforced concrete containers. Compared to the implementation plan of the decommissioning, this number is an improvement of 2 FCCs, which represent considerable economic savings.

ACKNOWLEDGMENTS

This study has partially been supported by the grants of the Slovak Research Development Agency no. APVV VV-20-0300 and DS-FR-19-0014 as well as the funds of the Scientific Grant Agency of the Ministry of Education of Slovak Republic No. VEGA 1/0615/21.

REFERENCES

[1] M. Myslík, Skladovanie aktivovaných fragmentov tlakovej nádoby VVER-440 z vyraďovania JE V1 (In Slovak), STU, Bratislava, 2020, FEI-104410-80673

[2] Javys a.s., "Decommissioning of NPP V1", https://www.javys.sk/sk/cinnosti-spolocnosti/vyradovanie-je-v1

[3] Javys a.s. "Štúdia realizovateľnosti nakladania s komponentami PO JE VI" (In Slovak), Javys a.s., Bratislava, 2013

[4] ORNL, SCALE Code System Version 6.2.2 (Oak Ridge National Laboratory, ORNL/TM-2005/39, 2017, 2003) p.2747.

[5] M.B. Chadwick, et.al, "ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology", Nucl. Data Sheets, 107, 2006, pp. 2931-3060