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**BIBLIOGRAPHIC SYNTHESIS OF THE EXPERIMENTAL AND  
NUMERICAL GERMAN AND FRENCH RESEARCH PROGRAMS  
CONCERNING SLUG IMPACT**

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## **Keywords**

slug impact, alpha mode, PWR, steam explosion, BERDA, FLIPPER, SKIPPY, CASTEM-PLEXUS

## **Abstract**

Slug impact is considered as a potential risk for PWR power plants in case of a severe accident. A loss of coolant can cause the degradation of the core and its melting. By falling down in the water remaining in the lower plenum, the corium transfers quickly its energy to the water which vaporizes and causes a steam explosion. The explosion may be powerful enough to accelerate upwards all the materials above the explosion zone and causes, in turn, a slug impact.

During this process, the mechanical energy of the explosion is transformed into kinetic energy for the slug. If the slug is energetic enough, it can crush and fail the upper structures. Then the mixture of slug and upper structure pieces may hit the upper head vessel. The impact may fail the upper head or part of it and thus create missiles, flung upwards thanks to the remaining energy.

The slug impact is studied by the german and french research centers FZK and CEA-Saclay. FZK aims at the quantification of the maximum mechanical energy which would not lead

to fail the upper head. They investigate this issue by means of the reduced-scale experiments BERDA.

The transfer of the experimental results to reactor dimensions using scale factors are based on similarity laws whose validity is checked thanks to the german test-facilities FLIPPER. The understanding of the slug material influence and the extrapolation to the corium is investigated with the french test-facilities SKIPPY.

In order to deepen the understanding of the impact process and to extrapolate the experimental results to other combinations of parameters, corresponding theoretical work is being performed with the code ABAQUS for the impact of solid structures and with the code CASTEM-PLEXUS developed by CEA-Saclay for the impact of liquid projectile against solid structures.

## **1 Introduction**

Since the Three Miles Island accident (Libmann, 1996) on the 28<sup>th</sup> march 1979 and the publication of the Rasmussen report known as WASH 1400, steam explosion and slug impact have been considered as a potential risk for PWR nuclear power plants.

Among the hypothetical severe accidents induced by a core melting, steam explosion and slug impact have been intensely studied (Theofanous (a), 1995) and is still studied for future reactors (Livolant, 1997) (Van Goethem, 1997) (Van Goethem, 1999) because it might lead to potentially catastrophic environmental consequences caused by an early and massive containment failure.

Assuming that the loss of coolant caused a degradation of the core and its melting, the principal accident sequences can be summarized as follows (Theofanous, 1987) (Abolfadl, 1987) (Amarasooriya, 1987) (Lucas, 1987) (Jacobs, 1993).

1. The corium relocates from the core area into the lower plenum and premixes coarsely with the water. The jet of corium fragments under the action of hydrodynamic forces in large drops whose characteristic size is 1 cm. The thermal exchanges are limited by the presence of a vapor film surrounding the corium drops and by the water depletion.

2. A trigger causes a fine scale fragmentation of the drops. This fragmentation strongly increases the corium thermal exchange surface and allows the explosive vaporization of the water due to high energy transfers between the corium and the water (Berthoud, 1988).

During a very short initial period, the pressure rises quickly in the premixing zone and expands through the lower head. The resulting dynamic forces may reach a magnitude sufficient enough to fail the lower head vessel. This venting relieves partly the explosion pressure.

3. At the same time, the interaction zone expands against the core support plate, accelerating upwards all the materials above the explosion zone. During this process, the mechanical energy of the explosion is transformed into kinetic energy for the slug.

The slug may be energetic enough to crush and fail the upper structures. The mixture of slug and upper structure pieces may hit the upper head vessel.

The impact may fail the upper head or part

of it and thus create missiles, flung upwards thanks to the remaining energy.

4. If the missile are not resisted by shields or massive obstacles, they might be hurled against the containment roof and penetrate or seriously damage it. This scenario would lead to an  $\alpha$ -mode failure.

The potential risks due to an  $\alpha$ -mode accident are globally quantified through Probabilistic Safety Assessment studies (Theofanous, 1987) (Turland, 1995) (Theofanous (b), 1995). These studies are based on the understanding and the evaluation of each key event thanks to the realisation of small and medium scale experiments and the development of numerical models and codes.

In Europe, several research centers have been working on steam explosion for several years. The whole work has been organized so as to share out the study set necessary to fully understand the matter between the different research centers and countries and to pool the final knowledge.

The European research program is divided into three main themes: the premixing phase, the steam explosion and the slug impact. For each issue, test-facilities and numerical computations have been realised. This paper comprises a review of the test-facilities and codes available at the present time in Europe for slug impact.

## 2 General description of the research program

The slug impact concerns the acceleration upwards of the molten corium and its impact on the reactor pressure vessel upper head. In a very energetic event, the head could fail and missiles could be formed endangering the containment integrity.

This matter is studied by the german and french research centers FZK and CEA-Saclay. FZK aims at quantification of the maximum mechanical energy which would not lead to fail the upper head. They investigate this issue by means of the reduced-scale experiments BERDA.

The transfer of the experimental results to reactor dimensions using scale factors are based on similarity laws whose validity is checked thanks to the german test-facilities FLIPPER. The understanding of the slug material influence and the extrapolation to the corium is investigated with the french test-facilities SKIPPY.

In order to deepen the understanding of the impact process and to extrapolate the experimental results to other combinations of parameters, corresponding theoretical work is being performed mainly with the finite element code CASTEM-PLEXUS developed by CEA-Saclay.

### 3 Test-facility BERDA

The experiment BERDA (Figure 2) has been designed to estimate the slug carrying capability of the Reactor Pressure Vessel (Kornelson, 1998). 1:10 scaled replica models of the upper part of a RPV are used. The model consists of the upper part of the vessel and its bolts. In most of the tests, models of the upper internal structures were also included. They were made either of the original material or of a reduced strength and ductility material to simulate better the accident conditions (Krieg, 1999).

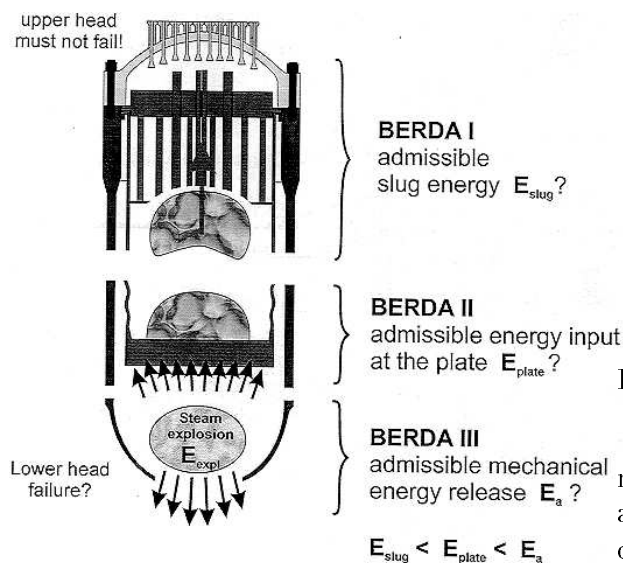


Figure 1: The investigation program BERDA

The investigation program (Figure 1) with the experiment BERDA plans to study successively (Krieg, 1998):

1. the admissible kinetic energy of a corium slug which can be safely withstood by the vessel head,
2. the admissible mechanical energy which can be applied to accelerate the support plate upwards,
3. the admissible mechanical energy release of the assumed in-vessel steam explosion, including the energy dissipation by the lower head behaviour.

During the BERDA I tests, three kinds of projectiles were thrown up against the model upper head: solid projectile, slugs of lead spheres and slugs of liquid metal (Krieg, 1997).

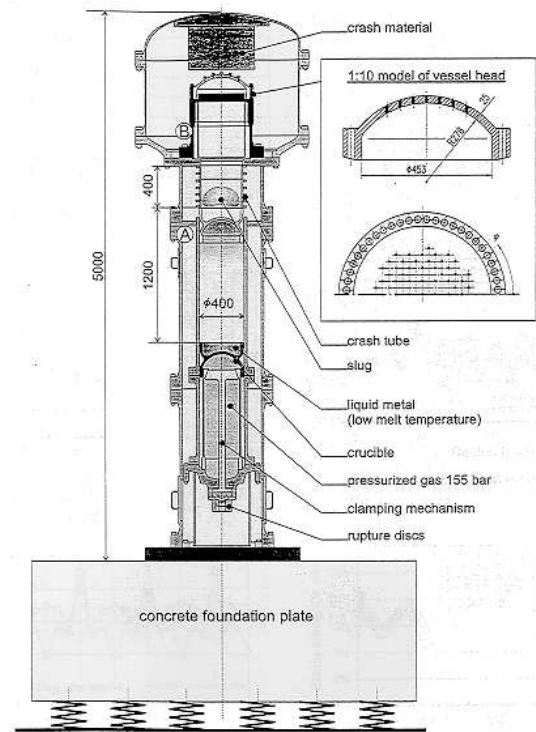


Figure 2: Test-facility BERDA

The liquid slug is simulated by the lead-bismuth alloy, known as Wood's metal, which has approximately the same density as the molten core material but whose melt temperature is only 58°C. The liquid metal is contained in a crucible which is propelled upwards by pressurized gas. 80 kg of Wood's metal are accelerated up to 130 m/s. The crucible is stopped by a tubular crash structure, while the slug finally hits the model.

In order to minimize slug dispersion, the Wood's metal is hold together by a thin-walled second crucible which is destroyed during the impact against the model. The whole facility is mounted on a heavy base plate supported by springs in order to carry the dynamic loads.

The facility is instrumented with photoelectric beams to measure the liquid slug velocity and strain gauges to know the impact force at the bolts and the head deformation.

#### 4 Interpretation of the BERDA tests

In parallel with the experiments, corresponding calculations were performed using the available codes. To simulate the BERDA test with the solid projectile, a small circumferential sector including one half of a bolt was discretized and calculated with the finite element code ABAQUS (Dolensky (b), 1997) (Figure 3). An explicit time integration scheme and non linear material properties for head, bolt and projectile were used. The comparison with the experimental results concerned forces, strains in the bolts and the head and the momentum transferred by the bolts to the projectile.

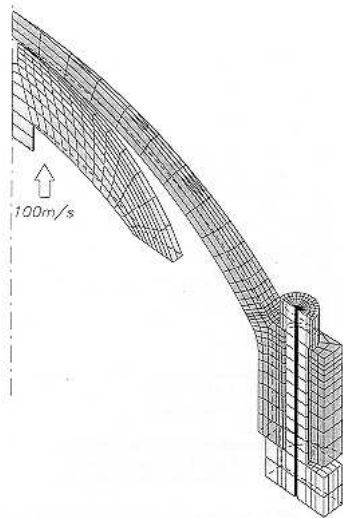


Figure 3: Discretization of vessel head and projectile for calculation with ABAQUS

The BERDA tests involving liquid slug could hardly be described by classical Eulerian or Lagrangian methods because the slug is seriously distorted during the impact and it finally

splashes. Thus, other methods have to be applied. The one implemented in the CASTEM-PLEXUS code (Hoffmann, 1984) (Robbe, 1999) developed by the CEA allows to discretize the liquid slug by an assemblage of discrete particles (Bung, 1993) (Figure 4).

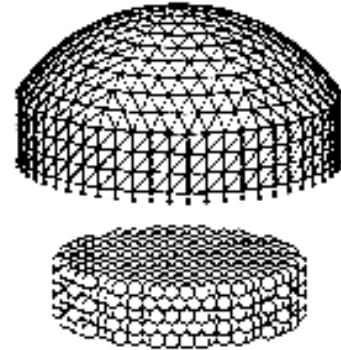


Figure 4: Discretization of the liquid slug impact problem for calculation with CASTEM-PLEXUS

In each time step, other particles interact with each other or with the boundaries (Figure 5). The density is only a function of the average distance between the particle and the neighbouring ones. Pressure is related to density through the constitutive law for perfect fluid. The forces between the particles are related to pressure through geometrical considerations.

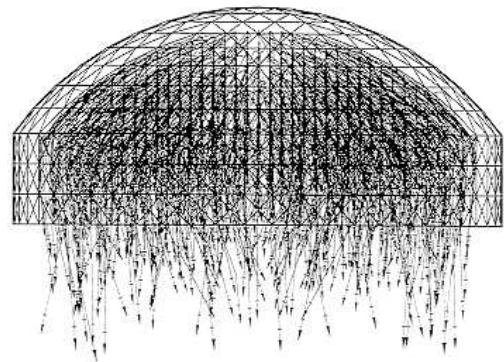


Figure 5: Calculated paths of the slug particles during the impact against the head

The vessel head was modeled with thin shell elements and the bolts by truss elements clamped at their lower end. In the first calculations, the vessel was represented by a rigid structure.

The pressure loading obtained from CASTEM-PLEXUS was used to calculate the head response and its deformation with ABAQUS (Dolensky (a), 1997) (Figure 6).

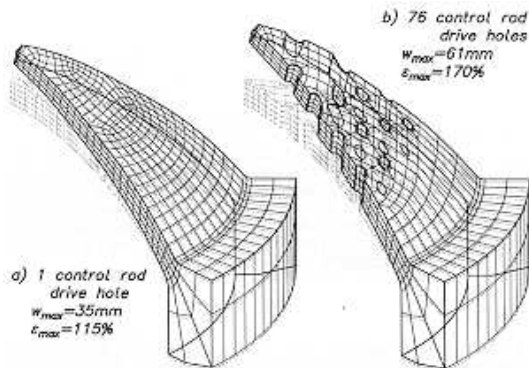


Figure 6: Influence of the control rod drive holes on the plastic head deformation

The following calculations included improved laws to represent the material behaviour. The vessel head and bolts were successively modeled by a linear elastic law (Dolensky (a), 1997), an elastoplastic law (Dolensky (b), 1997) and finally by an elastoplastic model including hardening (Strub, 1998).

For all the computations (Abaqus and Castem-Plexus), the comparison with test results concerned the impact forces in the bolts, the momentum transferred from the liquid slug to the RPV head, the permanent deformation and the strains.

In order to attempt to determine the maximum slug impact that a vessel head was capable to withstand without failing, theoretical assessments were realised for each local cause of energy dissipation. The global dissipation by deformation of the Upper Internal Structures, vessel bolts, by local flow through the UIS and by splashing during the impact was first estimated from small-scale experiment results and expert considerations (Krieg, 1995). It was more precisely estimated later (Krieg, 1999) with the help of the results of the BERDA I test facilities including all or part of the UIS.

As the phenomena inducing energy dissipation are too complicated for a detailed numerical analysis, a coarse uniaxial model has been

developped by FZK (Hirt, 1997). The model SIMSIC represents the different geometrical components by point masses. The internal structures are represented by one mass if they are still intact and another if they failed. Both masses change with time according to the progression of the failure. The model allows to study the influence of failure loads, flow resistance, inertia and further parameters of the upper internal structures (Dolensky (b), 1997).

## 5 Test-facility FLIPPER

Conversion of the BERDA results to the reactor scale is accomplished using similarity theory (Krieg, 1999). Since the basic equations allow only an approximative description of the problem, the scaling rules have also an approximative character. Therefore, the validity of the elementary scaling laws is to be studied experimentally. In the FLIPPER program, simplified structures of different scales are deformed plastically by a fluid impact in order to investigate the validity and accuracy of the scaling laws for strains, stresses, fracture conditions and hardening (Krieg, 1995).

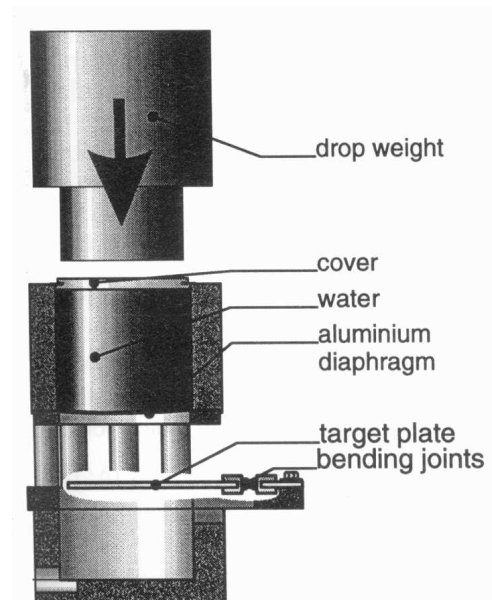


Figure 7: Test-facility FLIPPER

The equipment (Figure 7) mainly consists in a drop hammer, a water container and a stiff frame where the test specimen is fixed. The water container is closed at the bottom by an aluminium diaphragm and at the top by a swim-

ming cover. When the hammer hits the cover, the whole fluid is accelerated downward. The water cover is retained in the reservoir and the drop weight is decelerated by a shock absorbing material (Stach, 1997).

At a certain distance below the container, the specimen is positioned. It consists of a rectangular target plate connected to the frame by two bending joints. When the liquid hits the plate, all the plastic deformation is concentrated in these joints.

Several experiment series were performed at three different scales. The scaling involves the target plate and the bending joints, the water reservoir, the drop hammer and the supporting frame. In all tests, water is used as the impacting fluid.

The primary measurement concerns the permanent rotation of the target plate after the experiment (Figure 8). Additional observations are done concerning the drop hammer speed using laser beams, the deformation and rupture of the diaphragm and the water flow using a high speed camera.

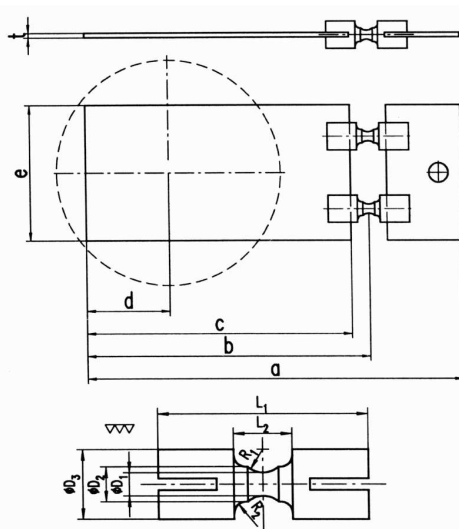


Figure 8: Target plate and bending joints

According to the bending joint material, more or less significant size effects are observed. Their origin depends on the solid material behaviour: strain rate sensitivity and properties of plastic flow (Stach, 1997) (Jordan, 1998).

Simple theoretical calculations were done to evaluate approximatively the bending moment and the plate deflection due to the water impact. They also tried to assess the sensitivity of the deflection to a modest variation of the force amplitude in order to understand the reason of the experimental result scatter (Stach, 1995).

Additional computations with a structural dynamics model aim at assessing whether the viscoplasticity of the bending joint materials is the primary cause for the observed scale dependence of the permanent target plate rotation and whether geometric variations in the transient loading of the plate are sufficient to explain the scatter of nominal identical experiments (Stach, 1997).

## 6 Test-facility SKIPPY

As the impacting fluid used in the BERDA tests-facilities is Wood's metal - a material different from the corium which is liable to impact the vessel upper head of a real reactor, the transposition of the experimental results to the reactor involves to estimate the influence of the slug material on the impact force.

The SKIPPY1 experiment consisted in dropping cylindric projectiles of different sizes and made of different materials on a plate supposed rigid. The objective was to quantify the influence of the projectile nature on the maximum value of the load transmitted to the impacted structure. The fall height was kept constant: 0.5 m. The materials used for the projectile were: water, dry or wet sand, glass marbles or a mixture of liquid and glass marbles. These tests proved that the homogeneity and cohesiveness of the impacting material had a non-negligible influence on the maximum value of the transmitted load (Strub, 1997).

The SKIPPY2 (Figure 9) experiment aim was to test the influence of the nature and size of the specimen at larger scales. Therefore the tests were realised on the experimental tower ORION devoted to the study of guided drops. The tested specimen was kept steady on a heavy base plate. It was crashed by a rigid dropping hammer whose fall was vertically guided by

the experimental tower ORION. This disposal avoided the interferences observed in SKIPPY1, due to vibrations of the impacted plate.

The specimen was initially hold together in a cylindric shape by a weak crash-proof container whose contribution was negligible during the impact. This container allowed a good control of the specimen shape in order to make easier the test interpretation.

The drop height was maintained constant for all the tests and the same variety of materials was used for the specimen as in SKIPPY1. The scale effects were investigated by modifying the sand cylinder sizes and mass (Krieg, 1998).

The facility was instrumented with piezoelectric collectors placed below the impacted mass in order to measure the impact force. The mass displacement was also noted and a video of the tests was realised. These tests ended in 1999.

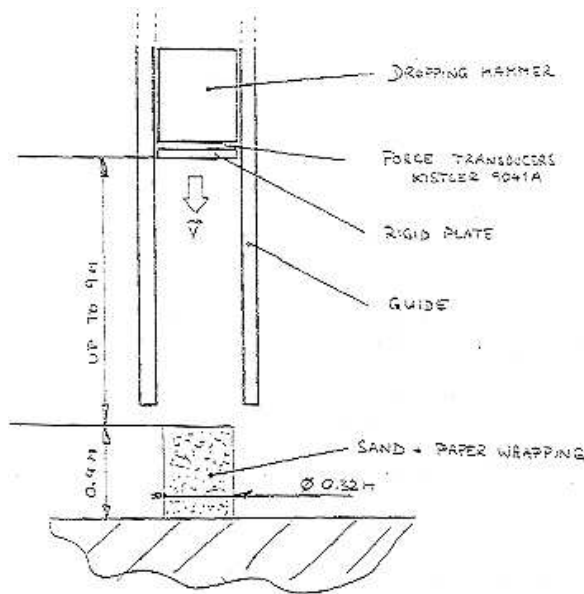


Figure 9: Test-facility SKIPPY2

As the SKIPPY results showed that the impact force depended on the material nature, it was essential to develop and validate a numerical tool able to predict the impact of any material. When the corium properties are better known, this tool will be used to evaluate the RPV upper head response due to a corium jet impact.

Once more, the particle model of the CASTEM-PLEXUS code was used. The code was useful on the one hand for scoping calculations (Strub, 1997) to foresee the result magnitude of the SKIPPY tests and then to make easy the collector calibration and on the other hand for the interpretation of the realised tests (Luzeau, 1998). The interpretation of the SKIPPY results gave the opportunity to validate the method, to adjust the model parameters, to earn precision and to adapt the model to represent better the sand behaviour.

The heavy base plate is represented by cubic elements supposed either not able to get out of shape, or linear elastic. The impacting hammer is modeled by a material point with the appropriate diameter. The sand cylinder is described by more than 10000 spheric particles (Figure 10). The sand constitutive law is assimilated to a porous material one. The bottom and the lateral surface of the cylindric base plate are embedded. The calculation starts with an initial velocity of the hammer equal to the one when it arrives next to the sand heap top after its free fall.

The comparison with the experimental results concerns the impact force, the impulse, the projectile displacement and speed. Both results are in a good agreement.

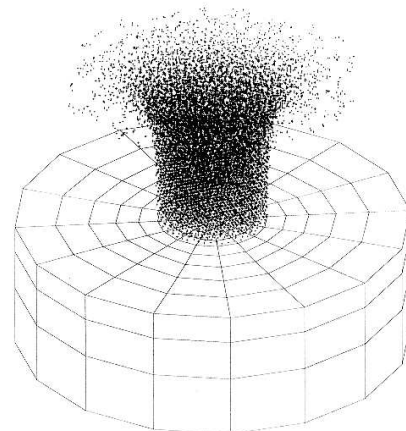


Figure 10: Deformed shape of the sand particle set during the impact calculated with CASTEM-PLEXUS



## 7 Conclusion

The European investigation program relative to slug impact involves mainly the German and French research centers. In order to understand the behaviour of the PWR upper head and its capacity to resist to an internal missile, a huge program was undertaken by FZK. The CEA-Saclay role consists in interpreting the experimental results and in realising small additional tests. The research program is mainly based on experimental tests and complementary computations.

The major test-facility is the BERDA experiment which simulates small-scale tests of a slug impact on a upper head mock-up. Several kinds of projectiles were thrown against the head to estimate its resistance. Two complementary analytical experiments are used. FLIPPER estimates the validity of the similarity laws by deforming plastically the hinges of a plate impacted by water. SKIPPY assesses the influence of the slug material by dropping several kinds of projectiles on a rigid plate.

In order to extrapolate the experimental results obtained on small-scale test-facilities to the real reactor and to deepen the understanding of the phenomena, computations were carried out. The code ABAQUS was used for computing the impact of solid projectiles in the tests BERDA. The code CASTEM-PLEXUS was used for computing the impact of liquid projectiles in case of the tests BERDA and for modeling the experiment SKIPPY.

## 8 Acknowledgment

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