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KIT-JIMEC Experiments to Investigate Jet Impingement on the Ablation of Core Catcher Bottom

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ABSTRACT

In 2019, the research activities of KIT in the field of experimental severe accident research on fast reactors were concentrated on the European ESFR-SMART project. Within this project two large-scale JIMEC (Jet Impingement of Metallic Core-Catcher) experiments have been performed to investigate the thermal ablation kinetics of an internal core catcher material in a SFR (Sodium-Cooled Fast Reactor). Besides this, the planning work for LIVE-ESFR tests to study the interaction between the corium simulant and the sacrificial simulant of the core catcher started. It has been decided to construct and build a new test vessel with down-scaled geometries similar to SFR core catcher design.

The actual safety design of a SFR in the case of a postulated severe accident includes removing the corium from the core by corium transfer tubes and collecting the corium in a core catcher in the lower head. One threat scenario of the core-catcher integrity is a high ablation rate by the impingement of a metallic corium jet on the core catcher surface. Experimental data is needed to simulate this ablation behaviour under prototypical conditions including a long impinging duration and high jet temperature. Under such conditions, the insights of a yet insufficiently studied behaviour when a molten pool is created ("pool effect") at the impact point could be obtained. Therefore, the ITES-SAR (Institute for Thermal Energy Technologies and Safety - Severe Accident Research Group) team has adapted the existing MOCKA test facility to perform two JIMEC experiments in the frame of the European ESFR-SMART project. JIMEC-1 and JIMEC-2 tests are two large-scale tests with 1 ton of metallic mass. The objectives of the experiments are to deliver experimental data on the interaction of melt jet parameter and erosion dynamics in prototypical materials and conditions. The melt jet parameters such as jet temperature, jet velocity and jet diameter, and the erosion dynamics including the erosion velocity and the timing of pool effect are obtained. The experimental results will be used for developing new correlations which could be used in codes for simulation of the ablation kinetics for SFR core catcher concepts.

1 INTRODUCTION

A feature of the actual SFR design to avoid the accumulation of a corium pool in the core in a postulate severe accident situation is relocating the corium melt via corium discharge tubes to the core catcher located at the bottom of the reactor vessel. However, the discharge of corium in form of a high energetic jet would threaten the integrity of core-catcher bottom plate via impingement. The ablation rate is dependent on the material of melt, material of the substrate and outer jet parameters such as temperature and velocity. From the aspect of long-term stability of the core-catcher, a metallic core-catcher is more favourable than a ceramic one. As a metallic corium melt could relocate firstly, a special problem of the corium jet impingement in a SFR core-catcher would be a metallic melt jet impinging on a metallic core-catcher. A high ablation kinetics is expected of the impingement of a metallic jet on a metallic substrate, since there is no formation of a refractory crust in the ablation front as it would be in the case of an oxide melt jet. At the same time, the melting temperature of the metallic core-catcher material is lower than the melting temperature of a ceramic refractory material. Furthermore, the fact the liquid metal ablates similar material preferably via formation of low-temperature eutectics can additionally accelerate the ablation rate.

Ablation by jet impingement as general topic was studied experimentally and theoretically in many reactor accident scenarios. VESTA program investigated experimentally the impingement of oxide melt jet on metallic vessel wall of LWR reactor vessel lower head [1]. KAJET at KIT evaluated the concrete ablation kinetics by metal and oxide melt jets for LWR severe accident conditions [2]. CORVIS experimental program investigated the ablation of a steel plate by liquid iron generated from thermite reaction [3]. The results of these experimental programs have shown the trend of high ablation rates, however, the kinetics of the ablation process was not systematically studied. The ablation of the lower plenum support plate of a RPV was analytically studied by Chen et al. [4], whereas the accumulation of melt instead of melt jet was the major interest of the study. The jet impingement of corium in SFR without corium discharge tubes is simulated by wood´s metal jet on wood´s substrate in [5]. The results shown penetration of two parallel structure materials by wood metal. More detailed analysis of metallic jet impingement on a metallic plate was given by authors in [6-8]. Important ablation kinetics were obtained at the jet temperature range up to 1700 °C with jet diameter of 10 - 30 mm. In their experiments, a thin metallic target was molten through, before a deep melt pool could be formed in the ablated pit. Systematic study on pool effect was undertaken in [9] with the simulant water and ice as jet and substrate material with large difference in the Pr and Ra number comparing to prototypical metallic melt. The Nu number of ablation in this simulant experiment is about 1/3 to 1/6 of the prediction by metallic jet given by [7].

For SFR conditions, metallic melt jets with higher temperature (~ 2000 °C or higher) and larger jet diameter are foreseen. This would lead to a faster ablation of the core-catcher material and a deeper ablation pit in the core-catcher. To withstand the foreseen ablation, a thick core-catcher bottom plate (about 40 cm) is necessary. A positive effect in a deep pit can be generated as the accumulated corium pool inside the deep pit slows down the jet velocity and thus the initial ablation rate (phenomena known as “pool effect”). However, this phenomenon has been studied very little in the past and the dimensionless number correlations do not exist in the literature. In this scope, beyond the fundamental study with simulant jet and substrate material, large-scale experimental tests are necessary by using important representative parameters (e.g. jet material, superheat, geometry, velocity and the core-catcher material) for ESFR severe accident conditions.

KIT has high expertise and equipment in the generating metallic melt via thermite reaction. This technology was applied in experimental programmes for ex-vessel corium cooling COMET-Concept [10], KATS and ECOCATS [11] on melt spreading, and recently in the MOCKA experiments on molten corium concrete interaction (MCCI) in 2D and 3D geometry in concrete crucibles [12]. The JIMEC-1 and JIMEC-2 experiments have been performed on the site of the MOCKA test facility to reproduce the jet impingement behaviour on a thick substrate representing the bottom plate of SFR core-catcher. Experimental results will be used for developing new correlations, which could be used in the codes for simulation of the ablation kinetics for ESFR core catcher concepts.

2 JIMEC TEST FACILITY

The JIMEC test facility includes the thermite reaction crucible, the pouring spout for redirection of oxide melt after the outflow of the metallic melt, the oxide melt collector and the test substrate, see Figure 1. The jet falling height from the crucible outlet to the substrate are 1.08 m and 0.94 m in JIMEC-1 and JIMEC-2 respectively. The thermite reaction crucible can contain 3 tons of thermite material. The melt outflow opening at the crucible bottom is 40 mm in diameter for JIMEC-1 and 30 mm in diameter for JIMEC-2.. After ignition, the thermite reaction is usually completed within 30 to 60 seconds. In the crucible, the metallic melt is separated apart from the oxide melt and locates beneath the oxide melt due to its higher density. A thermocouple above the outflow opening detects the end of the thermite reaction. Based upon this thermocouple signal, the opening mechanism is immediately manually activated and the outflow of the metallic melt starts. At the end of metallic jet flow, the pouring spout is moved to the outlet position and the oxide melt is redirected to an oxide melt collector next to the crucible.

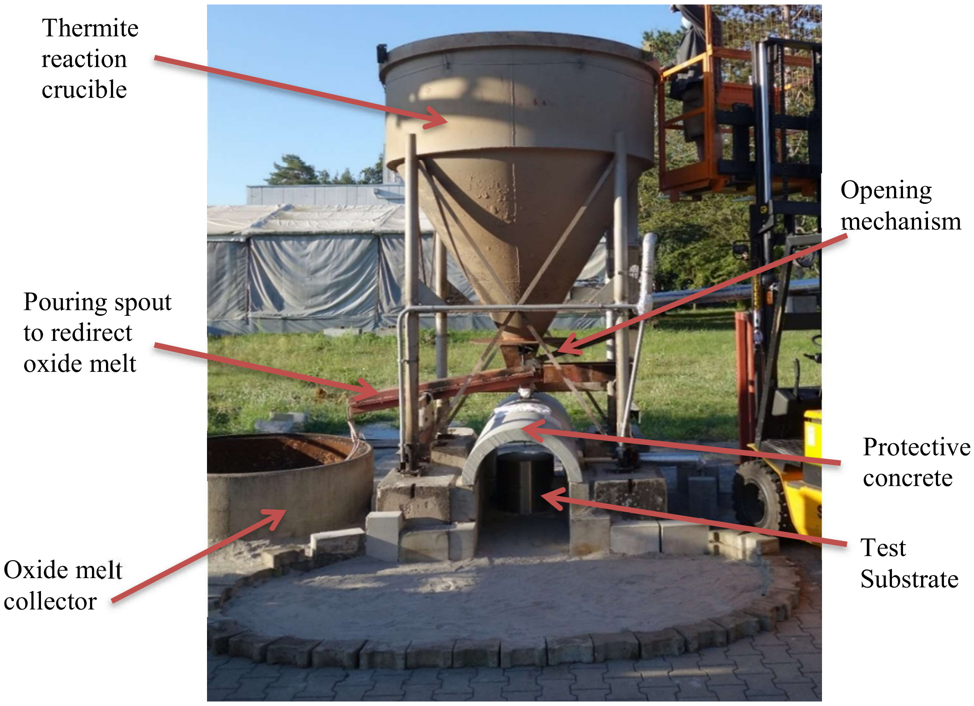


Figure 1: JIMEC experiment setup

The test substrate is a cylindrical stainless steel block with 416 mm in height and 425 mm in diameter (Figure 2). The material of the substrate is X5 Cr Ni 18 10. The melting temperature is 1450°C. To detect the ablation process and substratum temperature, 41 type K thermocouples in stainless steel sheaths (up to 1370 °C) were mounted on an “Instrumentation plate”, theses were installed inside the substrate.

About 2000 kg Al-Fe_3O_4 based thermite with the addition of stainless steel components, mainly Cr and Ni, are used for the generation of 1000 kg metallic melt with stainless steel composed of about 18 % Cr and 10 % of Ni. The temperature of the molten thermite products is about 2000 °C.

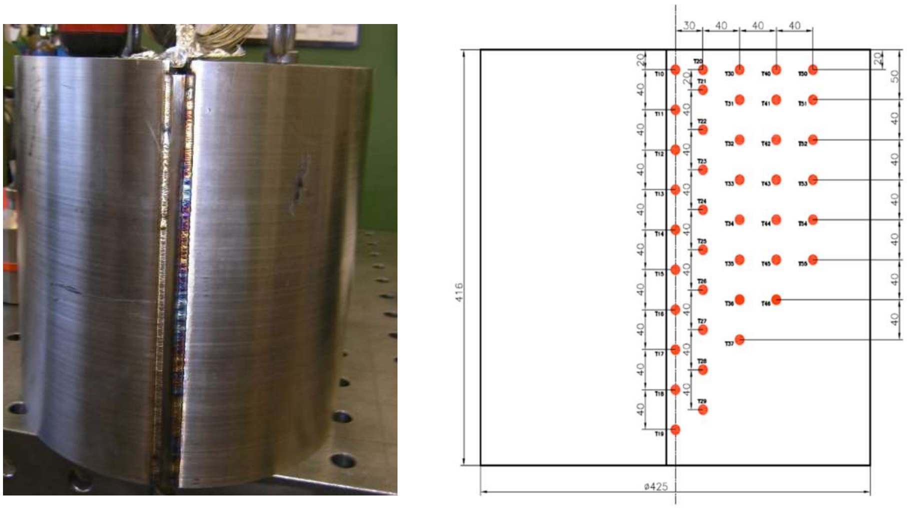


Figure 2: The substrate material. Left: 40 cm height cylindrical substrate made of stainless steel; right: the thermocouple positions (in red points) inside the substrate

Table 1: parameters of metallic jets in two JIMEC tests.

	Fall height from outlet to substrate, m	Jet diameter at substrate, mm/ time period, sec	Mass of metallic jet, kg	Jet velocity at substrate, m/s	Form of the jet at the substrate
JIMEC-1	1.08	26.4→36.3 / 0 - 5	960.7	5.07	Compact jet
JIMEC-2	0.94	20.3→29.8 / 0 - 25.6	998.5	4.78	Compact jet with swinging

3 ABLATION PROCESS

3.1 General description of metallic jet

In both experiments, the metal melt jet kept in most time coherent. No breakup of the jet flows was detected. In JIMEC-1, the duration of the metallic melt jet was 31 s for the outlet diameter of 40 mm. In JIMEC-2, the duration of the metal melt jet was 55 s for the outlet diameter of 30 mm. The initial diameter of the metal melt jet enlarged in both experiments due to the ablation of the outlet nozzle made of ZrO_2. The jet diameters, fall heights, metallic melt masses, and jet velocities are given in Table 1. In both experiments, the metal melt jet temperature could be measured with a pyrometer. The metal melt jet temperature was in both experiments in the range of 2000 to 2100°C.

3.2 Ablation dynamics

The ablation velocity in the substrate can be obtained based on the measurement abruption of the thermocouples inside the substrate. In the course of the impingement, a strong splashing jet turns to be quiescent as the jet material could be firstly retained in the pool in the ablated pit, and subsequently the mixture of the jet material and the ablated substrate flowed over the upper edge of the pit. The ablation was slowed down after this transition. The slowdown of ablation is the so-called pool-effect, which begins after the transition. Figure 3 shows the video pictures of the jet before and after the pool effect. The ablation dynamics are given in Table 2 and depicted in Figure 4.

Table 2: Ablation dynamic parameters

	Timing on the stop of jet splashing, [s]	Timing on the ablation front at 380 mm depth, [s] (short before melt through)	Av. ablation veloc. before pool effect, [mm/s]	Av. ablation veloc. After pool effect, [mm/s]
JIMEC-1	18.0	30.80	17.3	7.0
JIMEC-2	14.5	33.15	18	6.74

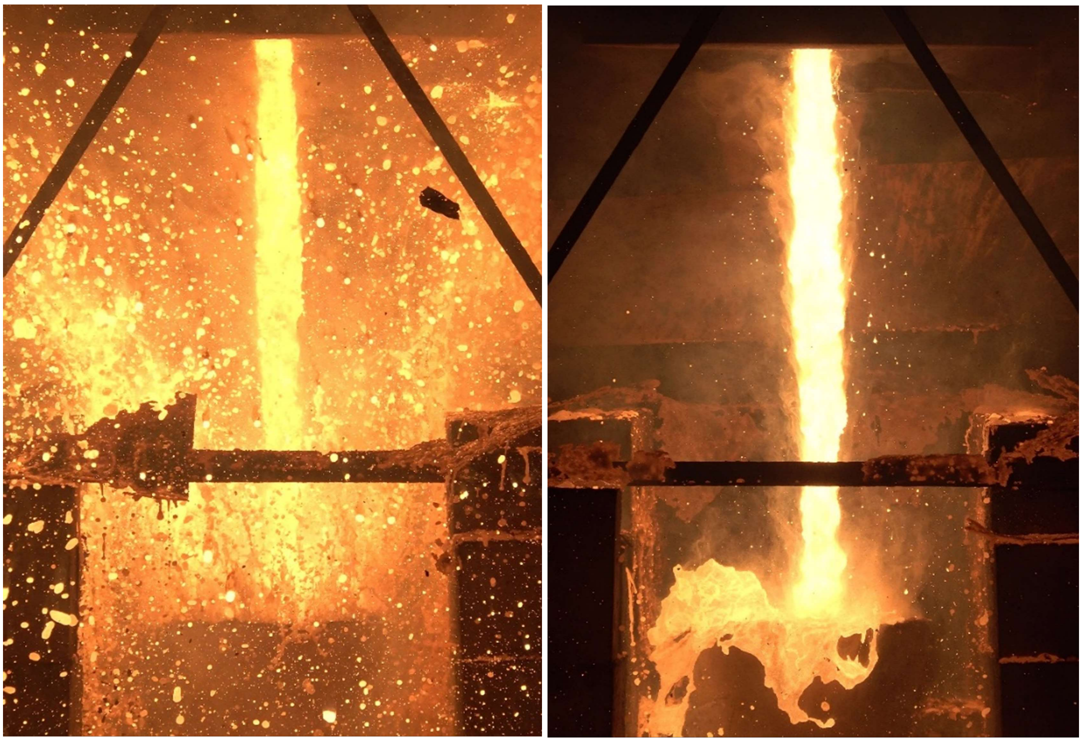


Figure 3: Jet impingement during JIMEC-1 test. Left: before the pool effect, right: after the pool effect.

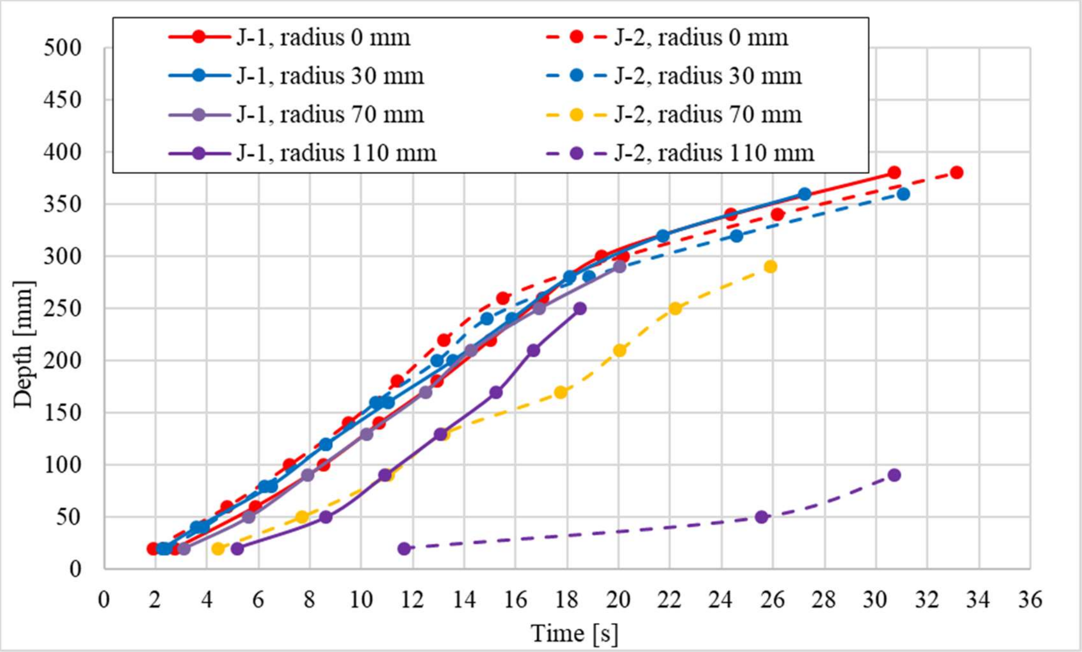
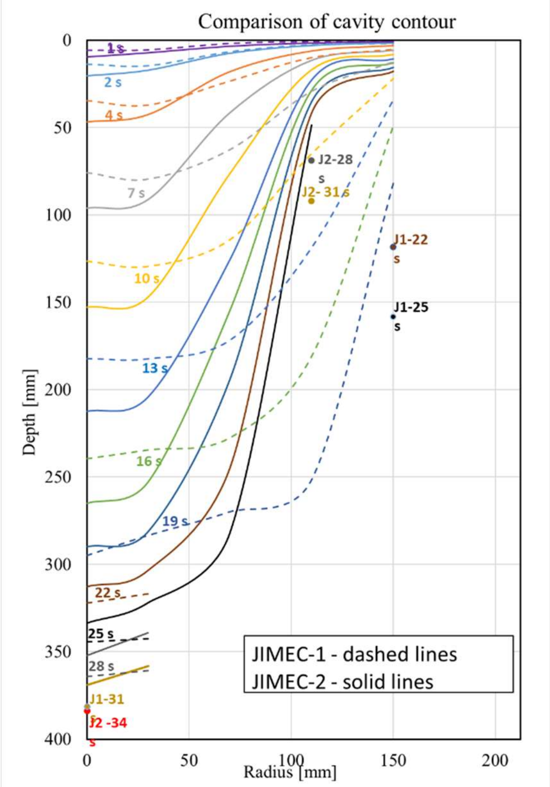


Figure 4: Ablation depth during jet impingement of JIMEC-1 and JIMEC-2 tests



(a) progression of the cavity contour during jet impingement

(b) JIMEC-I post-test cavity

(c) JIMEC-2 post-test cavity

Figure 5. Ablation cavity contours during impingement (left) and after the test (right).

The ablation contour progression during the impingement and the post-test ablation pits are shown in Figure 5. In both tests, the bottom of the 416-mm thick substrate was penetrated. During the JIMEC-1 test, a melt through at the middle level of the right side, very probably occurred after the termination of the metallic flow, resulted in a melt outflow via this position. The hole at the bottom was obviously closed again by the solidified melt underneath the substrate, leaving the liquid metal below the side hole solidified inside the cavity. However, the contour of the ablation under the solidified metal can be recognized, and is marked in red line in Figure 5(b). During the JIMEC-2 test, the bottom was ablated through in 42.96 seconds firstly at the cable tunnel for the thermocouples at the substrate bottom, subsequently the melt flowed out through the two holes at the bottom instead of over the upper edge.

3.3 Ablation characteristics

The most relevant literature describing the impingement of a metallic jet on a metallic substrate was given by Sato et al [7]. In this study 316 stainless steel is the substrate and jet material. The span of jet temperature was 1610 °C to 1710 °C, of jet diameter was 10 mm to 20 mm, of jet velocity was about 3.1- 3.7 m/s and the thickness of the substrate was 10 mm to 50 mm. The empirical Nu correlation and the ablation velocity, V_m, are given in Eq. (1) and Eq. (2) respectively. The substrate in Sato´s study is however too thin to initiate the pool effect. JIMEC experiment applies higher jet temperature and velocity, larger jet diameter, and thicker substrate than the conditions in this literature. The first step of the analysis of JIMEC experiments is to compare the ablation dynamics before the pool effect with the predictions of SATO. In Table 3 the heat transfer parameters are given and the ablation velocities are compared.

$$Nu = 0.0152\, Re^{0.92} Pr^{0.8} \tag{1}$$

$$V_m = \frac{0.0152 \rho_j Cp_j (T_j - T_{mp.s}) Re^{-0.08} Pr^{-0.2}\, V_j}{\rho_s \left[L + Cp_s\,(T_{mp.s} - T_s)\right]} \tag{2}$$

$$h_{eff} = Nu \cdot k_j / D_j \tag{3}$$

$$q = h_{eff} \cdot (T_j - T_{mp}) \tag{4}$$

For the heat transfer calculations, following physical properties in the operational temperature are applied.

Jet parameters:

T_j	Jet temperature, °C	2020
D_j	Jet diameter at substrate, mm	36 (J-1); 27.8 (J-2)
ρ_j	Density, kg/m³	6400.3
k_j	Thermal conductivity, W/(mK)	29.95
μ_j	dynamic viscosity, Pa·s	$2.027 \cdot 10^{-3}$
Cp_j	Thermal capacity, J/kg/°C	750
Pr		0.05075

Substrate parameters:

T_s	Temperature, °C	20
T_{mp}	Melting point, °C	1435
L	Heat of fusion, J/kg	289000
Cp_s	Thermal capacity, J/kg/°C	469

Table 3: Ablation heat transfer characteristics before pool effect.

	Re $_j$	Nu	h_{eff} (HTC)	q (heat flux)	$V_{m,\,cal}$	$V_{m,\,exp}$
			W/(m²·K)	W/m²	m/s	m/s
JIMEC-1	$5.82 \cdot 10^5$	281.7	$2.32 \cdot 10^5$	$1.36 \cdot 10^8$	0.01804	0.0173
JIMEC-2	$4.2 \cdot 10^5$	208.8	$2.25 \cdot 10^5$	$1.31 \cdot 10^8$	0.01744	0.018

The ablation rates in JIMEC experiments before the pool effect is in very good agreement to the SATO´s equations given in Eq (2). This gives the confidence that the applying range of SATO´s equation can be extend to a higher jet temperature (up to 2050 °C) and to higher Ra and Nu, which are the prototypical conditions of the jet impingement on the SFR-core catcher. The heat transfer coefficient (h_{eff}) and heat flux (q) are calculated according to Eq. (3) and Eq. (4) respectively.

4 SUMMARY

Large-scale jet impingement tests with prototypical reactor conditions on metallic core catcher in SFR severe accident application have been carried out at KIT in the framework of EU H2020 ESFR-SMART project. The experiments demonstrate the ablation dynamics of a metallic jet with high temperature and velocity on metallic core-catcher bottom substrate. Very high ablation rates are observed that the penetration of the substrate took only about 30-35 secs. The jet diameter, which are different in the two tests, have no distinguished influence on the axial ablation rate, although the higher lateral ablation with large jet diameter is apparnent. Pool effect leading to reduced ablation rate occurs at the moment that ablated pit is deep enough to hold the melt materials inside. The Nu number and the ablation velocity of the experiment achieve very good agreement with the predictions of the early study by Sato. The timing and the ablation dynamic of the pool effect remain as the objective of the future study.

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