Learning from 1970 and 1980-Era Sodium Fire Experiments

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Abstract. Evaluating the risks posed by sodium fires would be an essential part of any modern sodium fast reactor safety evaluation. Sodium fires introduce large thermal loads on the structures in containment, and can drastically increase containment overpressure. Likewise, in the case that sodium from the primary heat transfer system is ejected into containment, the sodium fires would also be source of airborne fission products. Validated computational tools that can model these phenomena would of course be required to carry out the safety analyses on any new proposed reactor. That being said, in their development, it should be noted that there is a substantial amount of experience that was gained in the 1970s and 1980s on when there were large sodium fast reactor development programs around the world. Many of the fundamental safety questions that need to be addressed in modern safety codes have already been explored in the past, and there is a huge amount of value in re-visiting the experimental and theoretical work that has already been done. This paper discusses an effort to retrieve and re-examine research that was carried out in the 1970s and 1980s by the French *Institut de Protection et de Sûreté Nucléaire* (IPSN), and to use it to improve our understanding of sodium fires and fission product transport in containment, with the goal of improving the ASTEC-Na severe accident code.

Key Words: sodium fires, severe accident modeling, historical archives, knowledge preservation, ASTEC-Na.

1. Introduction

The original sodium fast reactor (SFR) concepts date back to the 1950s and 1960s, which were followed by large programs in the 1970s and 1980s in France, Japan, Russia, and the United States to build commercial-scale SFRs. Many of these programs were abandoned in the 1990s, but a considerable amount of work was done prior to that in order to demonstrate the technologies and to support their safety cases. There is renewed interest in SFR technology with the advent of Gen-IV concepts [1], along with a continued push towards improving the safety standards of the designs.

Evaluating the effects of sodium fires in containment would be an essential part of any modern safety evaluation because of the risk of thermal load of the structures, of containment overpressure, of sodium aerosol production, and of the fact that sodium fires would be a source of airborne fission products. Validated computational tools able to simulate the in-containment phenomenology are then necessary for a reliable estimation of the source term to the environment. ASTEC-Na, for example, has been under development at the *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN) as an extension of the light water reactor safety code ASTEC [2] to SFRs. Considerable effort has been put into ASTEC-Na with the European JASMIN project as well [3-4]. In order to aid and expedite the development of ASTEC-Na, gain a better understanding of sodium fire phenomenology in general, and guide future research and development efforts, a substantial amount can be learned by re-visiting the experimental and theoretical work that was done in the 1970s, 1980s, and early 1990s.

This paper discusses efforts that have taken place over the past several years by IRSN to retrieve and re-examine past experimental work that was carried out at the Cadarache research center in France. Different sodium fire programs are outlined, and are linked to new theoretical analyses and modeling efforts. The general process of working with archival materials, and some of the challenges associated with exploiting past results, are discussed as well. By and large, these efforts have been extremely valuable because of the breadth and depth of the past programs, and the difficulty is replicating the same type of work today. The main purpose of this paper is to share this experience, and underline how important it is to preserve, maintain, and actively use the knowledge that was generated in the past.

2. Knowledge Preservation Process

2.1.Historical Context

A very extensive sodium fire R&D program was carried out in France over a 20 year period between the mid-1970s and the mid-1990s. The history of this program is closely linked to its larger SFR development programs in the country, starting with the 40 MWt Rapsodie research reactor (operation 1968-1983), moving on to the 250 MWe Phénix demonstration unit (operation 1974-2009), and finally to the 1200 MWe SuperPhénix prototype reactor (operation 1986-1998) [5-6]. Liquid sodium metal is a very reactive material that bursts into flame when it comes into contact with air, and so a sodium fire R&D program was a necessary part of the French SFR development plans. For the most part, the work was carried out by the *Institut de Protection et de Sûreté Nucléaire* (IPSN), the predecessor of IRSN, which at the time was a division within the French *Commissariat à l'Énergie Atomique* (CEA). Early experiments focused on small and medium scale pool fires and spray fires, while later experiments looked at both larger scale fires and special issues, like sodium-concrete interaction, fission product behavior, atmospheric release, and fire extinguishment. Computer codes were always developed in parallel to the experimental programs, and used the experimental results for their validation, verification, and qualification.

The French SFR program, however, has had a complex history. The Rapsodie and Phénix reactors were built, commissioned, and operated quite successfully. SuperPhénix, on the other hand, had a lot of problems in its commissioning, had a poor operational record after its startup in 1986, and had large cost overruns. In addition, there was a lot of political opposition to the project post-Chernobyl, which compounded the situation, and ultimately, the French Government decided to cancel the project in 1998 [5]. Without a reason for continuing, the research programs into sodium fires were all stopped at this time as well.

In 2006, however, the French Government decided to re-invest in SFR development, and this time with the goal of producing a Generation IV reactor that could help consume the country's stockpiles of transuranic wastes. This initiative transformed into the ASTRID reactor design, and research and development into that project conducted by CEA, AREVA, and EDF have been ongoing ever since [7]. Early efforts in the ASTRID project, however, focused on developing a novel core design (actinide burning configuration, improved safety, reduced positive void reactivity) and exploring alternative power cycle fluids (nitrogen or CO2 cycles to eliminate the possibility of sodium-water reactions).

Renewed interest in sodium fires started again later one, such as with the European JASMIN program, which was aimed at developing a sodium version of the ASTEC severe accident code [3-4]. This program, launched by IRSN, was started in 2011 and was mainly dedicated to ASTEC-Na code modeling and validation. This still left about a 15 year gap between the termination of the first-generation sodium fire research programs and the start of new programs. As a consequence, a lot of the first-generation researchers that had worked on sodium fires had retired, resulting in a significant loss of expertise.

2.2.Methodology for Uncovering Past Expertise

Although the original results from the French sodium fire R&D program have all been carefully archived within the organization, due to the politics of the time, not a lot had been shared or published externally. However, as original researchers retire, the details, and even the existence of certain experiments starts to fade from the corporate memory. This gap makes it more difficult to re-examine and re-use past results, and means that a larger effort has to take place in order to identify and understand what was there.

The process for uncovering old experimental results has involved:

1. Identifying the experiments and retrieve the corresponding experimental reports
2. Digitize the experimental results
3. Enter the document and experimental results in dedicated databases

The process for uncovering old codes and models has been similar to the process for uncovering experimental results, but has been slightly more complicated because it has depended on whether the source code could be found, and how compatible it was with modern computing systems. Broadly, though, the steps for uncovering codes have been very similar to the steps for uncovering experimental results:

1. Identify the codes and retrieve the corresponding source, executable and supporting documentation for different versions of the code
2. Enter the documents in dedicated databases
3. Assess compatibility of the source code with modern computing systems, re-compile and re-run codes, if possible

An essential important step is to actually go on and use that information in new studies once it has been recovered. There would always be opportunities to use the past experimental data to inform new experiments, to develop more systematic theories, or to validate computer codes. Likewise, even if old computer codes can't be directly incorporated into new codes, they can still provide a lot of insight into what sort of theory, numeric, and coding techniques could be used in new codes. Nothing is gained, however, if the only thing accomplished by uncovering archival information is to create database of archival information, since all would be accomplished is effectively copying the information from one place to another.

3. Past Sodium Fire Research

3.1.Experimental Programs

There were hundreds of individual sodium fire tests, as part of over 30 different programs, which were conducted by IPSN between 1973 and 1993. These programs, shown in Figure 1, covered the following themes:

- ***Spray fire tests*** were intended to study the fires that result from sodium being ejected into the air. They covered small-scale and large-scale tests, and where sodium was ejected at different speeds from differently sized orifices. These were mostly high flow, short duration tests meant to simulate ejections from core disruptive accidents, quantifying the pressure spikes in containment that would result, but a number also studied the type of fire that would result from smaller leaks in the secondary system.
- ***Pool fire tests*** were intended to study the thermal hydraulic effects of the fires once sodium had accumulated on the floor, and also study aerosolization rates of sodium

combustion products. They covered fires at a number of different scales, and were usually long duration tests lasting several hours.

- ***Contaminated pool fire tests*** were intended to study the release of fission products. A number of different important radionuclides, including species of iodine, cesium, ^{22}Na, ruthenium, cerium, and uranium, were all examined.
- ***Sodium-concrete interaction tests*** were intended to study the gases released from the thermal and chemical decomposition of concrete when it comes into contact with high temperature liquid sodium metal.
- ***Applied tests*** studied various practical aspects, and included tests for different extinguishment techniques, leak recovery techniques, and post-fire response techniques.
- ***Atmospheric release tests*** were intended to study what happens to the smoke from a sodium fire once it is released into the atmosphere, and examined deposition rates around the location of the fire, as well as the influence of local meteorology and release heights.

IPSN led the majority of the programs listed in Figure 3, but collaborated with other European organizations for some of the larger-scale experiments. The ESMERALDA program, for example, was a collaboration between IPSN and the Italian *Energia Nucleare ed Energie Alternative* (ENEA), as well as some French industrial partners. The TVMA program was a collaboration between IPSN, ENEA, and the *UK Atomic Energy Agency* (UKAEA). Likewise, the FS and FMA/FMI programs were collaborations between IPSN and the German *Kernforschungszentrum Karlsruhe* (KfK). Most of the work was performed by IPSN in facilities at the Cadarache research center in France, while a few were conducted at the KfK FAUNA facility in Karlsruhe, Germany. The different facilities include:

- CASTOR vessel – a 3.7 m^3 or 4.4 m^3 steel vessel, max pressure of 8 bars. Mostly used for small scale pool fires, contaminated pool fires, and sodium-concrete interaction tests.
- POLLUX vessel – a 3.7 m^3 or 4.4 m^3 steel vessel, max pressure of 8 bars. Mostly used for small scale spray fire tests.
- MERCURE vessel – a 22 m^3 steel vessel, max pressure of 3 bars. Used for small-scale spray fire and pool fire tests.
- FAUNA vessel – a 220 m^3 steel vessel, max pressure of 10 bars. Multi-purpose sodium fire facility in Karlsruhe, Germany that was commissioned by IPSN for a number of medium-scale spray fire tests.
- PLUTON vessel – a 400 m^3 concrete room, max pressure of 1.25 bars, equipped with mechanical ventilation. Used for medium-scale spray fire and pool fire tests.
- SATURNE vessel – a 2000 m^3 concrete tower, designed for natural ventilation with open panels near top of ceiling. Used for atmospheric release tests and compartmentalized spray fire tests.
- JUPITER vessel – a 3600 m^3 concrete room, max pressure of 2 bars, equipped with mechanical ventilation and spaces to perform smaller scale experiments. Used for large scale pool fire and spray fire tests. Also used for some of the applied tests, like extinguishment or leak recovery experiments.

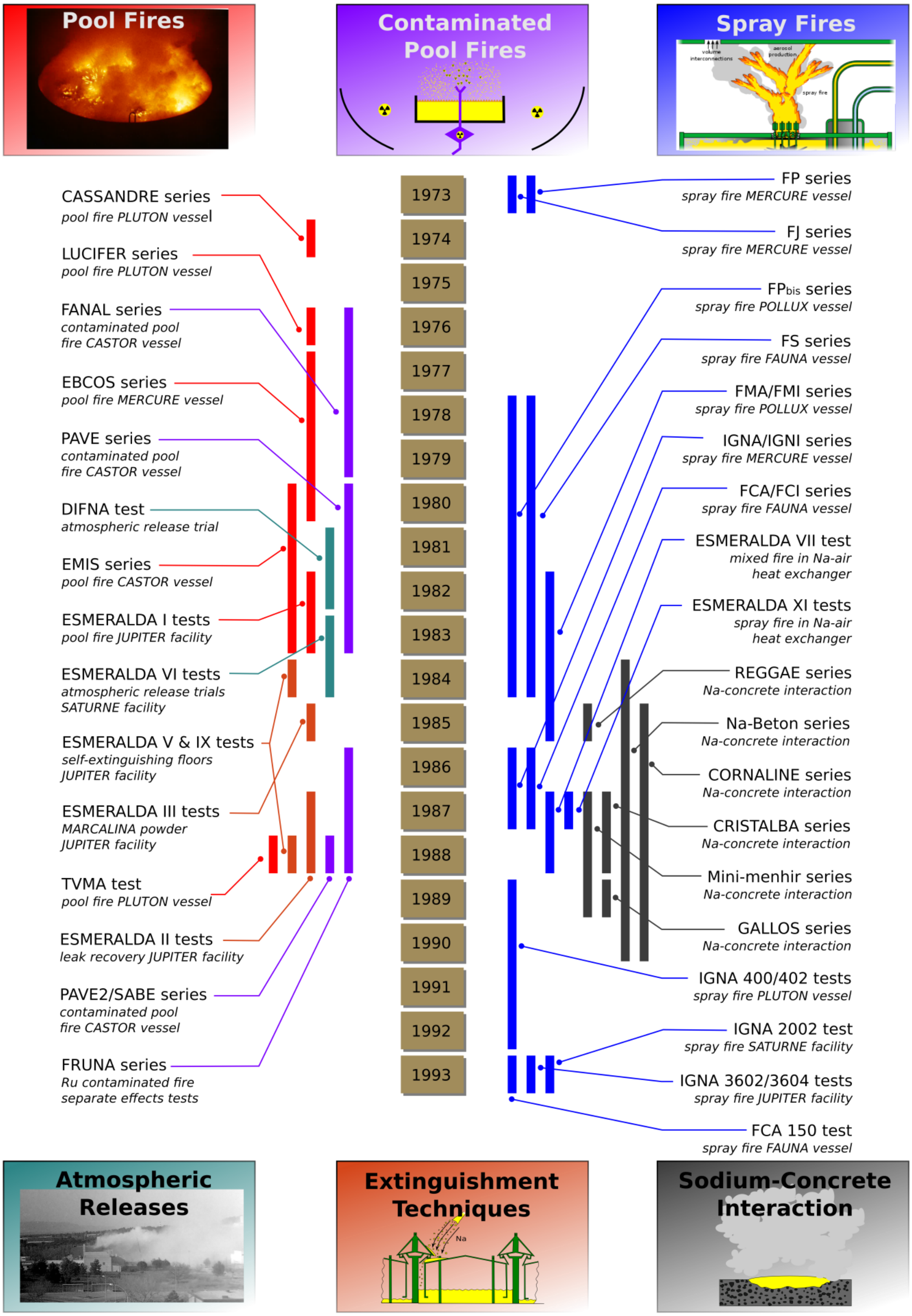


FIG. 1. Timeline of sodium fire experiments.

3.2.Accident Modeling Software

Incorporating what was learned from experiments into computer models was always an integral part of the French program.   These codes were developed from the 1980s onwards to calculate various aspects of sodium fire phenomena:

- FEUMIX [9] was designed to calculate the thermal-hydraulic consequences of sodium spray fires and pool fires. It is an integrated, lumped-parameter code capable of performing calculations on a whole containment. It was created in 1990, and last updated in 2000.
- PULSAR [10] was designed to simulate the thermal-hydraulic consequences of a sodium spray fire. It calculates the burning of sodium droplets in a two-dimensional field, and was created in 1982, and last updated in 2000.
- PYROS was designed to simulate the thermal-hydraulic consequences of a sodium pool fire in containment. It was a lumped-volume containment code, and was created in 1980, but abandoned in 1984.
- AEROSOLS was an aerosol physics codes designed to calculate the transport and deposition of aerosols throughout a containment volume. It was not an SFR-specific code, but was used for SFR applications from when it was created in 1980 to about 1985.
- ICAIRNA was designed to model the dispersion and deposition of sodium fire aerosols after their release into the atmosphere. It was created in 1984, but was only ever used to help study the ESMERALDA VI tests.
- SORBET was designed to calculate the thermo-mechanical behavior of a block of concrete. It was created in 1986, and although it was coupled to REBUS in 1987 to form RESSORT for sodium-concrete interaction, it remained a standalone code into the 1990s.
- REBUS was designed to calculate the chemical interaction between sodium and concrete, through Gibbs Energy minimization. It was created in 1986, but incorporated into RESSORT in 1987.
- RESSORT is a sodium-concrete interaction code.   It was created in 1987 essentially to couple the thermos-mechanical aspects of SORBET and the chemical interaction aspects of REBUS.

3.3.Major achievements of the French sodium fire R&D program

Prior to 1970, there hadn’t been any really detailed studies on liquid metal sodium fires, and how they differ from standard hydrocarbon fires. There certainly wasn’t enough information available to make comprehensive and supportable nuclear safety conclusions for SFR plants. However, the French program systematically addressed knowledge gaps and brought the state of the art for SFR-related sodium fires forward [8].

- ***Spray fire tests:*** This was one of the cornerstone pieces of the R&D program. Several sub-programs were dedicated to studying different aspects of the spray fires. Differences in flow rate, nozzle size and geometry, containment volume, ventilation rate, etc., were all studied, and the experiments were conducted at larger and larger scales. One important thing that was shown was that as the sodium injection rate increased, the overall combustion efficiency often dropped. For these large sodium fires, the total combustion rate depended more on oxygen transfer from the air rather than the amount of sodium being ejected. These lessons were incorporated into the FEUMIX code, and FEUMIX solved this by utilizing an empirical parameter, $S_i h$, which captured the combination of the flame surface area and convective heat transfer coefficient. Figure 2 gives an example of FEUMIX applied to the IGNA 3.2 experiment. FEUMIX [9], the global sodium fire code, as well as the more specific 2D axisymmetric code PULSAR [10], were particularly successful with regards to the modeling of sodium spray fires. They were extensively validated, and achieved their main goal of being able to be used in SFR safety analysis (e.g., Varet et al., 1996 [11], for SuperPhénix).

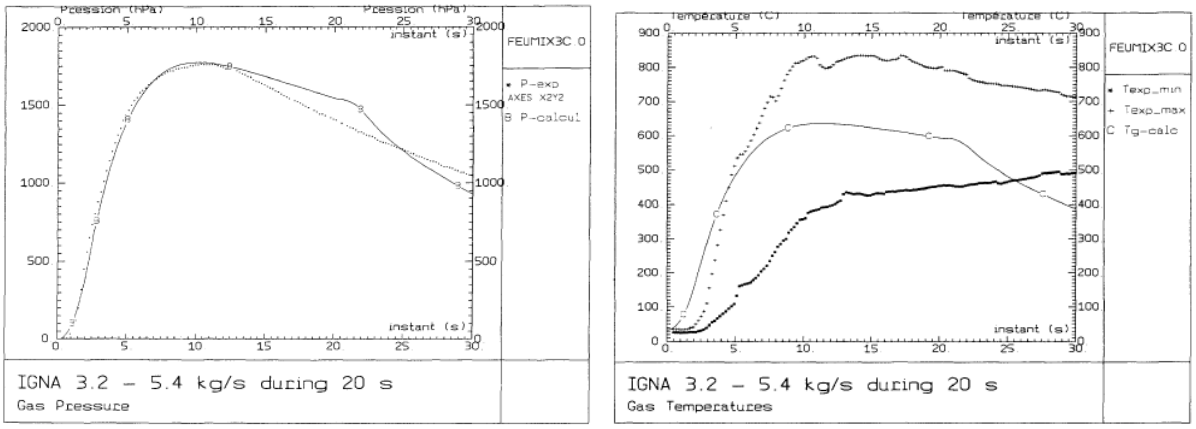


FIG. 2. FEUMIX pressure and temperature results on a calculation of the IGNA 3.2 experiment (22 m^3 vessel, 5.4 kg-s^{-1} spray over 20 s with 550°C sodium) [9].

- ***Pool fire tests:*** There were also a large number of pool fire tests that were conducted at several different scales. A lot of them were used to study the overall burning rate for pool fires, as well as ignition phenomena. Most of the time, sodium metal can ignite at 200°C or less. Initially, the combustion process is slow, with surface combustion being the primary mode. However, once the pool heats to above 500°C, sodium starts to vaporize more quickly, and the combustion starts to take place in a thin flame a few millimeters above the surface of the pool. Aerosol production also become more important at higher temperatures, but since the flame was always so close to the surface of the pool, only about 25% of the combustion product would usually be emitted into the air.

- ***Contaminated pool fire tests:*** The largest experiments in the world to ever have studied contaminated pool fires (using real radioactive products) were conducted as part of the French R&D program. They studied releases of Cs, I, Te, Ag, Sr, Ru, Sn, Sb, Ce, Zr, and U, and found that while most elements would be preferentially retained in the burning pool, cesium and iodine would be preferentially released into the aerosol phase. The iodine case is especially interesting because it is preferentially release from a burning pool, but preferentially retained in a pool in an inert atmosphere.

- ***Sodium-concrete interaction tests:*** This was an important applied aspect of sodium in the nuclear safety context, because sodium can interact with hydrates or steam in the concrete to produce hydrogen gas, which can then go on to explode. There was a lot of experimental work that was done to study this, and results were incorporated into the RESSORT code.

- ***Applied tests:*** Innovative firefighting technologies were successfully developed and tested as part of the French R&D program, like self-extinguishing "smothering tank" floors (which allowed sodium to flow into a closed subfloor compartment) or MARCALINA powder (which was a alkali carbonate-graphite mixture). Likewise, tests were dedicated to study re-ignition, which is an important practical consideration when re-entering a room after a sodium pool fire has self-extinguished.
- ***Atmospheric release tests:*** These tests were important demonstrations of the environmental consequences of the release of sodium fire aerosols, and showed, for examples, things like how far the plume would travel, how deposition rates depend on wind speed and humidity, and how vegetation would be affected in the areas surrounding the release.

4. New Uses for the Historical Knowledge

It is clear that the past sodium fire research program was very extensive. Efforts to retrieve all of this information have been ongoing since 2015. There is a huge amount of data to go through, and steps have already begun to start using results from the program in new studies.

4.1.Expediting the development of SFR accident modeling software

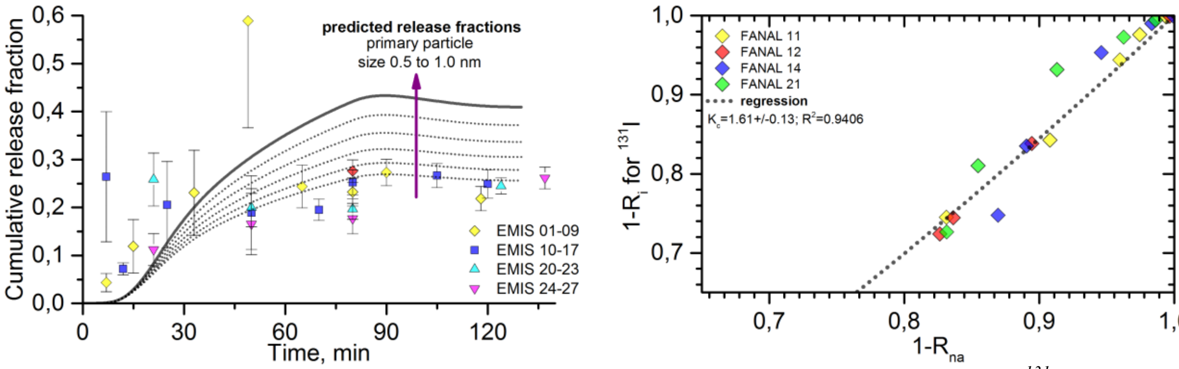
IRSN has been developing ASTEC-Na since the start of the JASMIN program in 2011. The code and the outcomes of the program are described in detail in Girault et al. (2017) [4], but it is a general severe accident code and is composed of several different inter-coupled modules that each calculate a different aspect of the accident or part of the plant (e.g., ICARE for core degradation, CESAR for primary/secondary thermal-hydraulics, CPA for containment thermal-hydraulics, SOPHAEROS for radionuclide and aerosol transport). For containment and source term analysis, the light water reactor version of the ASTEC containment module, CPA, was modified so that it could be applied to SFRs [12]. However, by the end of the program, the modified version of CPA could only model simple sodium pool fires. The historical FEUMIX code, however, was available at IRSN, and already contained a comprehensive suite of models for sodium spray fires, pool fires, and other aspects of SFR containment phenomenology.

The FEUMIX source code was also compatible with ASTEC-Na, and so in late 2015, efforts started to add the code to ASTEC-Na as a parallel containment module to the sodium version of CPA. Adding FEUMIX directly into ASTEC-Na precludes the need to recreate the spray fire modules in CPA. Likewise, since different aspects of FEUMIX had already been validated in the 1990s, this validation basis can be carried forward. All in all, using FEUMIX has greatly accelerated the development of ASTEC-Na, and with much less effort than completely redeveloping models from scratch. Plans are currently in place to publish papers on aspects of the spray fire and pool fire validation for FEUMIX. Something still lacking in ASTEC-Na is modeling of sodium-concrete interactions. Plans are in place, however, to examine RESSORT and attempt to incorporate it into ASTEC-Na as well.

4.2.Studies of basic phenomena from re-interpretation of experiments

An incredible amount of work was done in the past, not only to perform the sodium fire experiments, but also to develop comprehensive theories of the underlying phenomenology. With that being said, the theory was only developed up to a certain point, and certain gaps were never fully resolved. This was a generation ago, however. There have been a number of theoretical advances made by researchers around the world since then [13-16], and vast improvements in the speed and power of computational tools. This allows a new perspective and different tools that can all be used to make new theoretical advances using the historical experimental data.

For example, studies are being carried out in order to better characterize aerosolization rates from sodium pool fires. These are relied heavily on data collected from the EMIS experiments, and have resulted in the development of new theoretical models for how these processes occur (Figure 3a). Similar studies how radionuclides are released from sodium pool fires are being carried out as well, this time relying heavily of data collected from the FANAL experiments (Figure 3b). The vast amounts of data on sodium spray fires have also been synthesized in order to develop an improved empirical model on spray fire combustion. Plans are in place to publish results from all of these studies in the near future.



(a) cumulative aerosol release fractions, comparing predictions to measurements from the EMIS program.

(b) relationship between fractions of ^{131}I and sodium remaining in the pool from FANAL experiments.

FIG. 3. Example results taken from upcoming publications.

4.3.Enabling collaborations and benchmark studies

Another very important way that these past results can be used is through collaborative benchmarking studies. For example, the JASMIN program had an extensive benchmarking aspect to it, and involved organizations from several European countries [3-4]. Benchmarking exercises offer a platform that allows information and capabilities to be shared amongst different organizations, and often, countries respond in-kind with their own experimental results or calculations from their own computer codes. IRSN is planning on participating in other benchmarking studies in the future.

5. Conclusion

There were many important contributions on sodium fire safety that were made in the 1970s and 1980s, and they still address a lot of the important safety questions with respect to SFR containment phenomenology today. There is a huge amount of value in re-visiting this information, and this paper has described efforts to retrieve and re-examine the work that was done in France from about 1973 to 1993. The process of retrieving the information has been discussed, and extensive program has been summarized. Several ways that this information is being incorporated into new studies is also discussed in the paper, including its role in the development of the ASTEC-Na severe accident code.

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