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Abstract

Public safety and acceptance is extremely important for the nuclear power renaissance to get started. The Advanced Burner Reactor and other potential designs utilize liquid sodium as a primary coolant which provides distinct challenges to the nuclear power industry. Fire is a dominant contributor to total nuclear plant risk events for current generation nuclear power plants. Utilizing past experience to develop suitable safety systems and procedures will minimize the chance of sodium leaks and the associated consequences in the next generation. An advanced understanding of metal fire behavior in regards to the new designs will benefit both science and industry. This report presents an extensive literature review that captures past experiences, new advanced reactor designs, and the current state-of-knowledge related to liquid sodium combustion behavior.

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NOMENCLATURE

4S	Super Safe, Small, and Simple
ABR	Advanced Breeder Reactor
ABTR	Advanced Breeder Test Reactor
ASME	American Society of Mechanical Engineers
CRS	Central Receiver System
DOE	U.S. Department of Energy
FUANA	Beschreibung der Forschungsanlage zur Untersuchung nuklearer Aerosole
FBR	Fast Breeder Reactor
FBTR	Fast Breeder Test Reactor
GNEP	Global Nuclear Energy Partnership
HCDA	Hypothetical Core Disruptive Accident
IGCAR	Indira Gandhi Centre for Atomic Research
IHX	Intermediate Heat Exchanger
JAEA	Japan Atomic Energy Agency
JSFR	Japan Sodium Fast Reactor
KfK	Kernforschungzentrum Karlsruhe, Germany
LBB	Leak Before Break
LMFBR	Light Metal Fast Breeder Reactor
LOCO	Loss of Coolant Accident
LWR	Light Water Reactor
MOX	Mixed oxide
NPP	Nuclear Power Plant
ODS	Oxide dispersion Strengthened
R&D	Research and Development
SAPFIRE	Safety Phenomenology Tests on Sodium Leak,Fire and Aerosols
SFR	Sodium-Cooled Fast Reactor
SNL	Sandia National Laboratories
SSPS	Small Solar Power Systems
TRU	Trans-uranic

Chemical Formulas

CO_2	Carbon Dioxide
Na	Sodium
Na_2O	Sodium Oxide
NaOH	Sodium Hydroxide

Symbols

atm	Standard Atmosphere
bar	Atmospheric Unit
°C	Degrees Centigrade
cc	Cubic Centimeter
g	Gram
h	Hour
K	Degrees Kelvin
kg	Kilo-gram
lb	Pound
Pa	Pascal
Re	Reynolds Number
s	Second
m	Meter
mm	Millimeter
MWe	Megawatt Electric
psig	Pounds Per Square Inch
µm	Micrometer
vol	Volume
W	Watt

1. INTRODUCTION

The anticipated nuclear power renaissance hinges on public acceptance and a demonstrated treatment of potential safety issues, particularly for advanced reactor designs. The Advanced Burner Reactor (ABR) uses a liquid sodium primary coolant as do certain other advanced reactor concepts. In contrast to today's Light Water Reactors (LWRs), liquid-metal-cooled reactors present a unique risk; namely, potential metal fires involving the sodium coolant.

Fire is a significant contributor to total nuclear plant risk for current generation LWRs. Given "passively safe" advanced designs, some elements of plant risk will diminish substantially. Fires could represent the dominant risk contributor, especially given the unique characteristics of metal fires such as very high temperatures and fire suppression challenges. Fast breeder reactors all over the world use liquid sodium as a coolant and there has been experimental and analytical research done related to sodium fires as early as the 1950's. The research has included fundamental studies, work on droplet combustion, pool burning, suppression, and large-scale sodium fire experiments. However, there are gaps in our understanding of the basic combustion behavior and combustion mechanics due to the complexities involved. These gaps have led to little progress in understanding the basic combustion behaviors for sodium. (Makino 2006). Many of these same concerns were noted as far back as 1972 (Newman 1972).

New technologies have substantially improved fire computer modeling capabilities, but to apply these tools to a sodium fire will require some additional model development and validation work. Unfortunately, most of the experiments performed in the past cannot be used to support model development today. Clear definition of the experimental boundary and initial conditions are necessary to create the modeled conditions, and most of the experimental results lack this information. "Reports of precise conditions in experiments are rare in the literature," so the heat transfer evaluations have almost been impossible (Makino 2006).

This report includes four elements. First, a comprehensive review will define the current state of knowledge for metal fires. This will include actual metals fire experience in various applications. Second, an assessment of advanced reactor concept designs and identification of the unique metal fire safety and hazards was completed. A number of potential safety scenarios exist and will be grouped as to potential importance and representative physics to prioritize the specific research directions that will maximize breadth of applicability to emerging reactor designs. Third, a detailed review of sodium combustion research and potential approaches to the design and conduct of future experiments will be presented. Fourth, Appendix A presents an annotated bibliography of relevant literature identified during extensive literature review.

2. PREVIOUSLY RECORDED SODIUM FIRE ACCIDENTS

This chapter describes past sodium fires at nuclear reactors and other sodium facilities. The incidents discussed in this chapter were chosen to highlight the most significant issues surrounding sodium fires. These issues include design defects at startup (Monju), pipe bursts (BN-600), sodium spray fires (Almeria), and sodium-concrete interactions (ILONA)[1].

2.1 Monju Prototype Fast Breeder Reactor

The Monju Prototype Fast Breeder Reactor (FBR) first reached criticality in 1994. Powered operation began in 1995, and a series of power raising tests were performed, with a planned full-power test planned for June 1996. Monju is a loop-type 280 MW_e sodium-cooled reactor with mixed oxide fuel (Mikami 1996). During normal operation, the inlet and outlet sodium temperatures in the primary coolant loop are 397 °C and 529 °C, respectively. Sodium temperatures in the secondary coolant loop range between 325-505 °C.

During a scheduled power rating test (40% electrical power) on December 8, 1995, a high sodium temperature alarm sounded at the outlet of the secondary side of the intermediate heat exchanger (IHX) (Mikami 1996). At the same time, smoke detectors sounded in the same area, closely followed by a sodium leak detection alarm. Operators began normal plant shut-down procedures, but after increased smoke was observed 50 minutes later, it was decided to manually trip the reactor. This shutdown occurred approximately 1.5 hours after the initial alarms sounded.

Investigations later confirmed that a sodium leak and fire had occurred, ultimately, the source of the leak was traced to a damaged temperature sensor (pictured in Figure 1). The sensor consists of thermocouple wires housed in a protective well tube. It was found that the tip of the well tube had broken off and the thermocouple was bent at an angle of 45 degrees toward the downstream flow direction.

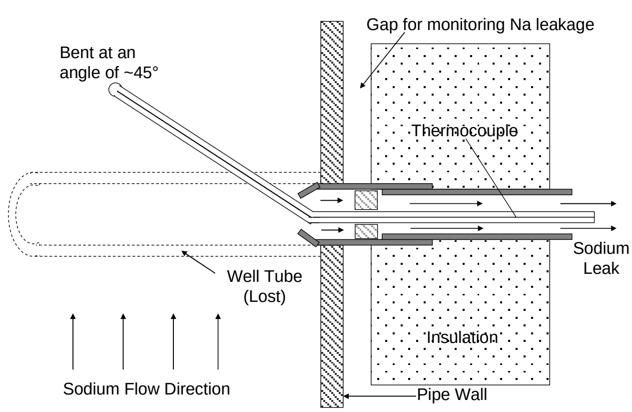

Figure 1: Sodium Leak Conditions at Monju. Adapted from (Mikami 1996).

[1] The acronym was not obtainable in the literature.

A microscopic inspection of the flow tube was performed to determine the root cause of the leak. It was concluded that the breakage of the well tube was caused by high cycle fatigue due to flow induced vibration in the direction of sodium flow. It was found that the problems were rooted in the design of the well tube. Although designers applied ASME standards to prevent resonant vibrations, they failed to take into account the sharp taper of the Monju tube design. As a result, the vortex-induced vibration could not be prevented. The design has subsequently been re-evaluated.

In addition to replacing all similarly designed temperature sensors, aspects of sodium fire response and emergency operation procedures were also modified at the Monju site. For example, the reactor will be shut down immediately if a sodium leak is confirmed in the future. A summary of the Monju Improvement Plan is shown in Table 1 (Mikami 1996). As this event was confined to the secondary coolant loop, there was no radiological release that affected either the general public or the plant personnel. However, it has resulted in over a decade of safety reviews in order to re-establish both technical surety and public confidence in the plant. The Monju plant is scheduled to resume operation in mid-2008.

Table 1: Monju Improvement Program. Adapted from (Mikami 1996).

Monju Improvement Program			
(1) Prevention of Sodium Leak • Replacement of the same type of temperature sensors • To secure safety of other types of sensors and other structures	**(2) Grasp Situation of Leakage** • Installation of new monitoring system • Improvement of fire detection & sodium leak detection systems	**(3) Suppression of Leakage** • Early shutdown of reactor • Early drainage of sodium	**(4) Mitigation of Effects by Leaked Sodium** • Improvement of ventilating system and early suspension of operation
(5) Review of Operation Management • Create supervisor for sodium technology • Create substantial education and training system • Strengthen emergency response organization	**(6) Safety Review** • Inspection of equipment and facilities • Learn from foreign experience and reflection	**(7) Confirm Safety of FBR system**	**(8) Improvement of sodium technology** • Establishment of Technology Development Center • Training of operation and maintenance

2.2 BN-600 Fast Reactor

The BN-600 sodium fast reactor began operation in 1980. It is part of the Beloyarsk nuclear power plant located in Zarechny town, Svedlovsk Region, Russia. The BN-600 is a pool-type 600 MW_e reactor with oxide fuel (Buksah 1997). The inlet and outlet sodium temperatures in the primary flow region are 337 °C and 550 °C, respectively. Sodium temperatures in the secondary cooling circuit range between 328-518 °C. During shutdown for refueling and maintenance, the primary coolant temperature is maintained in the 220-250 °C range.

Over its operational lifetime, the BN-600 plant has experienced numerous sodium leaks and associated fires despite the attention paid to leak prevention and fire safety. These leaks predominantly occurred in the early years of reactor operation. It was noted that out of the 27 documented sodium leaks, fire was observed in 14 cases. The causes of these leaks are listed below (Buksah 1997).

- Cracks in pipelines (6 cases)
- Failure of steam generator sodium valves (5 cases)
- Defects of flange joints (5 cases)
- Wrong sequence procedures of melting sodium in the pipeline (4 cases)
- Manufacture defect (3 cases)
- Holes made by personnel (2 cases)
- Sodium valve crack (2cases)

The largest primary sodium leak occurred on October 7, 1993. The total amount of sodium escaping during the event was estimated to be 1000 liters. The leak originated on the pipeline for sodium removal from the cold trap. The first indication of a leak was a short-circuit in the electric heating systems surrounding the pipe. Rising radioactivity was then detected in the exhaust ventilation air duct, triggering an automatic activation of isolation valves and an initiation of the fire-ventilation system. Despite these measures, radiation levels in the vent stack and reactor buildings continued to rise. As a result, the primary sodium purification system was completely isolated from the system and the reactor was shut down.

During the incident, plant personnel followed operating procedures and the sodium leak detection and fire mitigation equipment functioned as designed. Investigations later revealed that the cause of the leakage was the formation of two cracks in the neighborhood of a weld joint. The character of the cracks was indicative of a multi-cycle fatigue failure. It was determined that the root cause of the cracks was a closed valve not being fully tightened, resulting in a mixing of cold (130 °C) and hot (270 °C) sodium (Buksah 1997).

No site area or offsite contamination was registered due to this event, and there was no overexposure to plant personnel. The event was therefore classified as an anomaly (Level 1 on the International Nuclear Event Scale). After repair and clean-up and completion of a scheduled refueling, the reactor was returned to operation on October 24, 1993. Despite the negligible radiological consequences of this event, it was concluded that the next BN-type reactors should either keep all components inside of a reactor vessel or use completely jacketed pipes in order to have leak-tight protective barriers.

2.3 Almeria Solar Plant

The Almeria solar plant accident occurred in August 1986 in the Central Receiver System (CRS) of the Small Solar Power Systems (SSPS) test facility near Almeria, Spain (Luster 1996). The goal of the CRS was to demonstrate the feasibility of electrical power generation by the conversion of direct solar radiation into thermal energy and then into electrical power. Sodium was used as a means to store and transport heat to power conversion components of the plant.

Prior to the accident, the plant had been shut down to repair a leaking sodium valve. The valve was to be repaired under a gas pressure of 5.1 bar. During repair, an auxiliary helicoflex seal was used to maintain leak tightness. When the seal weld was cut about 2/3 of the way through, the helicoflex gave way. After several gulps of gas were expulsed, a strong sodium jet was ejected from the damaged valve, creating a violent sodium spray fire (Luster 1996).

Several personnel were injured during the initial release, but they managed to escape the room. Within a few minutes, operators attempted to release pressure from the system. However, the system was not energized. By the time emergency power was activated, enough damage had been done that the sodium jet could not be stopped by active measures. After approximately 30 minutes, the sodium spray damaged a nearby sodium storage vessel, relieving the system pressure and terminating sodium expulsion. The fire was extinguished within two hours.

Subsequent analysis of the fire region revealed surrounding materials reached temperatures as high as 1450°C, causing deformation and ruptures of steel piping and support structure, and melting of aluminum valve drive components (Luster 1996). Fire propagation was also investigated. Due to the nature of sodium fires (short flames, strong aerosol production), the propagation of the fire was limited to natural convection. This resulted in the destruction of 10 m^2 of roof. The fire door to a neighboring computer room was left open, and hot convective gasses caused fire to spread into this area as well. All other fire doors were closed, preventing further spread of the fire.

2.4 ILONA Test Facility

ILONA was a large sodium test facility to investigate natural convection in decay heat removal loops and was located at Bensberg, Germany (Luster 1996). The facility consists of a tower-shaped building of steel framework construction on a concrete basement. A sodium fire and a severe sodium-concrete interaction occurred in September 1992 at an auxiliary installation in the basement of the ILONA site.

At the time of the accident, storage vessels in the facility basement were being used to accept sodium from another plant at the site. The storage system consisted of two tanks with argon supply systems to supply pressure regulation and monitoring. The sodium to be transferred was originally frozen and so was melted with electrical heaters. Six hours into the heating procedure, a failure in the pressure regulation valves caused the control gas to become unavailable. The increasing gas pressure partially opened a gland plug, causing a slow (~0.2 kg/s) leak of sodium (Luster 1996).

Sodium continued to leak from the vessel for five hours, ultimately releasing 4300 kg. Spilled sodium came in contact with the concrete floor and walls, initiating a sodium-concrete reaction. The concrete floor was lifted by reaction products and the thermal expansion of the reinforcing steel. This expansion also lifted one end of the leaking vessel, ultimately inclining the vessel to the point of uncovering the opening and stopping the leak. The fire and concrete reaction continued for another nine hours after the leak was stopped.

Subsequent investigation revealed much about the sodium-concrete interaction and the thermal impact of hot reaction gas on unprotected concrete (Luster 1996). Sodium attacked the concrete to a depth of 39 cm. Maximum concrete temperatures of 900 °C were found. The reaction produced hydrogen, which burned and further increased the temperature of the storage vessel. The reaction products also increased the concrete volume. Figures of the cross sectional and horizontal extent of the sodium-concrete interaction zone can be found in Luster (Luster 1996). Thermal effects from the hot reaction gas also destroyed 50 m^2 of concrete wall, but did not compromise the structural integrity of the building.

2.5 Summary

Accident scenarios of past sodium fires at nuclear reactors and other sodium facilities are described in this chapter. The incidents were chosen to highlight the most significant issues surrounding sodium fires. The four sodium fires are compared in Table 2. The Monju reactor experienced a sodium leak resulting from a design defect during startup. The design was improved and new measures were adopted to better prevent and react to future sodium leaks. The BN-600 reactor experienced numerous sodium fires, primarily due to pipe and weld cracking. These primarily occurred in the initial years of reactor operation. The Almeria solar facility experienced a large sodium spray fire caused during a routine maintenance event. The ILONA facility experienced a sodium leak that resulted in significant sodium-concrete interactions. Each of these incidents demonstrates accident scenarios that must be accounted for when designing the next generation of sodium-cooled nuclear reactors.

Table 2: Comparison of Sodium Fire Accidents

Sodium Fire Accident Comparison		
Location	**Fire Type**	**Cause**
Monju	slow leak	design defect
BN-600	leak	weld cracks/fatigue
Almeria	spray	maintenance error
ILONA	sodium-concrete	valve failure

3. NEW REACTOR DESIGNS

This chapter introduces four proposed sodium-cooled reactor designs. These designs are first compared in Section 3.1 in terms of general operating characteristics, such as fuel type and efficiency. Section 3.2 then investigates potential causes of sodium leaks and fires in these new reactors during startup, operation, and maintenance. Finally, potential consequences of sodium leaks and fires are discussed in Section 3.3.

3.1 New Sodium Reactor Designs

Of all the new reactor designs proposed in the Generation IV program, sodium fast reactors have the largest experience base. A summary of existing sodium (and sodium-potassium) cooled reactors is provided in Table 3 (Berte 2007). Designers of the new class of sodium fast reactors, some of which are described below, have benefited greatly from the wealth of information acquired during the construction, operation, and decommissioning of the existing fleet.

Table 3: Summary of Sodium-Cooled Reactors Worldwide. Adapted from (Berte 2007).

Name	Purpose	Country	Coolant Ciruict Type	Power (MW_{th})	Coolant	Operation Period	Status (Dec. 2005)
RAPSODIE	R&D	France	Loop	40	Na	1967-1983	SE
KNK II	R&D	Germany	Loop	58	Na	1972-1991	DIP
DFR	R&D	UK	Loop	60	NaK	1959-1997	DIP
EBR I	R&D	USA	Loop	1.4	NaK	1951-1963	D
SEFOR	R&D	USA	Loop	20	Na	1969-1972	SE
EBR II	R&D	USA	Pool	62	Na	1961-1994	SE
FERMI 1	R&D	USA	Loop	300	Na	1963-1972	DIP
FFTF	R&D	USA	Loop	400	Na	1980-1992	SD
JOYO	R&D	Japan	Loop	140	Na	1977-2002	SD
BR-5/10*	R&D	Russian F.	Loop	10	Na	1959-2002	SD
SRE	R&D	USA	Loop	20	Na	1957-1964	D
HALLAM	R&D	USA	Loop	254	Na	1963-1964	D
BOR-60	R&D	Russian F.	Loop	60	Na	1968-	OP
FBTR	R&D	India	Loop	40	Na	1985-	OP
PHENIX	Prototype	France	Pool	563	Na	1973-	OP
PFR	Prototype	UK	Pool	670	Na	1974-1994	DIP
BN-350	Prototype	Kazakhstan	Loop	1000	NaK	1972-1999	DIP
MONJU	Prototype	Japan	Loop	714	Na	1995-	OP
S. PHENIX	Commerc.	France	Pool	3000	Na	1985-1998	DIP
BN-600	Commerc.	Russian F.	Pool	1470	Na	1980-	OP

* The BR-5 was upgraded in 1964; thereafter it was referred to as the BR-10. **
OP-in operation; SD-shut down; SE-safe enclosure; DIP-decom. in progress; D-decommissioned

The next generation of sodium-cooled fast reactors discussed in this chapter use one of two design types: pool-type and loop-type. In loop-type reactors, the primary coolant circulates through primary heat exchangers external to the reactor pressure vessel. Pool-type reactors, in contrast, have the primary heat exchangers (and in some cases the primary pumps) immersed in sodium inside the reactor pressure vessel.

Four reactor designs chosen based on availability of information are highlighted in this section. They are the Japan Sodium Fast Reactor (JSFR) by the Japan Atomic Energy Agency (JAEA), the Sodium-Cooled Fast Reactor (SFR) by Idaho National Lab (INL), the Super Safe, Small, and Simple (4S) reactor by Toshiba, and the Advanced Breeder Test Reactor (ABTR) by Argonne National Lab (ANL). A top-level comparison of these reactors is provided in Table 4.

Table 4: Comparison of Advanced Concept Sodium-Cooled Reactors

Advanced Concept Sodium-Cooled Reactors				
Reactor	**JSFR**	**SFR**	**4S**	**ABTR**
Developer	JAEA	INL	Toshiba	ANL
Flow Type	Loop	Pool	Pool	Pool
Power Output (MWe)	1500	varies	50	95
Plant Efficiency	~42%	~40%	37%	38%
Fuel Type	oxide	tbd	metal	metal
Max Sodium Temp (°C)	550	510-550	510	510

3.1.1 Japan Atomic Energy Agency Sodium Fast Reactor

The JSFR is a sodium-cooled, advanced loop-type reactor evolved from Japanese fast reactor technologies (Ichimiya 2007). It is a 1500 MW_e design with an estimated 42 percent plant efficiency. The JSFR design uses a trans-uranic, mixed oxide (TRU-MOX) fuel with a fast spectrum flux to achieve breakeven burn-up. A summary of plant specifications is provided in Table 5.

Table 5: JFSR Design Parameters. Adapted from (Ichimiya 2007)

JFSR Design Parameters	
Reactor Parameters	**Reference Value**
Electricity output	1,500MWe
Plant efficiency	Approx. 42%
Reactor Vessel	Loop
Primary sodium Temperature	395 ºC / 550 ºC
Power Conversion	Rankine
Fuel Type	TRU-MOX
Cladding Material	ODS (oxide dispersion strengthened) ferritic steels
Burn-up	~150 GWd/t
Conversion ratio	Break even (1.03), 1.1
Cycle length	26 months, 4 batches

According to the plant designers, three primary areas are being improved upon with this design. The first is the reduction of construction cost. This will be achieved by the adoption of innovative technologies, such as those being implemented in current Japanese construction, and through R&D efforts on several issues now in progress. The second is an improvement in core performance characteristics such as the breeding capability, actinide burning characteristics, fuel burn-up, and operation cycle length. The third target area of improvement, and the most relevant to this paper, is sodium safety. The potential drawbacks of sodium are to be overcome by system design features such as double-walled sodium boundaries in piping and heat exchangers. Thus, the designers conclude that plant safety and reliability can be ensured.

3.1.2 Sodium-Cooled Fast Reactor

The SFR system, developed for the Generation IV program, features a fast-spectrum, sodium-cooled pool-type reactor (Lineberry 2002). The fuel cycle employs a full actinide recycle with two major options. One option is an intermediate size (150 to 500 MW_e) sodium-cooled reactor with uranium-TRU-zirconium metal alloy fuel. The second option is a medium to large (500 to 1,500 MW_e) sodium-cooled reactor with MOX fuel. The sodium outlet temperature is approximately 550 °C for both options. A summary of reactor parameters is shown in Table 6.

Table 6: SFR design parameters. Adapted from (Lineberry 2002)

SFR Design Parameters	
Reactor Parameters	**Reference Value**
Rating (MWth)	varies
Plant Efficiency	Approx 40%
Reactor Vessel	Pool
Primary Sodium Outlet Temp	510 ºC – 550 ºC
Power Conversion	Rankine
Fuel Type	Oxide or metal alloy
Cladding Material	Ferritic or ODS ferritic
Burn-up	~150-200 GWd/t
Conversion Ratio	0.5-1.30
Cycle Length	varies

The SFR is designed for management of high-level wastes and, in particular, management of plutonium and other actinides. Important safety features of the system include a long thermal response time, a large margin to coolant (sodium) boiling, a pool-type primary system that operates near atmospheric pressure, and an intermediate sodium system between the radioactive sodium in the primary system and the water and steam in the power plant. The SFR's fast spectrum also makes it possible to use available fissile and fertile materials (including depleted uranium) considerably more efficiently than thermal spectrum reactors with once-through fuel cycles.

3.1.3 Toshiba Super Safe, Small, and Simple

The Toshiba 4S reactor is a fast-spectrum, sodium-cooled pool-type reactor (Sakashita 2004). Designs with power outputs ranging from 10 to 50 MW_e have been proposed. A moderate 33 percent efficiency is achieved with core outlet sodium temperatures of 510 °C. A summary of reactor parameters is shown in Table 7. The 4S reactor is intended for use in remote locations and to operate without refueling during its 30-year life. This is achieved in part with a metal fuel enrichment of 19.9 percent, just below the 20 percent definition of highly enriched uranium. The 4S has been compared with a nuclear "battery" because it does not require refueling. The lack of refueling would mean that the reactor's fuel supply would be a capital cost rather than an operating cost.

Table 7: 4S Design Parameters. Adapted from (Sakashita 2004)

4S Design Parameters	
Reactor Parameters	**Reference Value**
Electricity Output	50 MWe
Plant Efficiency	37%
Reactor Vessel	Pool
Primary Sodium Temp	355 ºC / 510 ºC
Power Conversion	Rankine
Fuel Type	U-Zr metal
Cladding Material	Advanced ferritic steel
Burn-up	34 GWd/t
Conversion Ratio	0.45
Cycle Length	30 years

3.1.4 Advanced Breeder Test Reactor

The ABTR is a sodium-cooled, pool-type reactor based on experience gained from the Experimental Breeder Reactor-II (Chang 2006). It is a 95 MW_e design with an estimated 38 percent plant efficiency. The ABTR was developed as a test bed for a similar commercial design-the Advanced Breeder Reactor. The ABTR design uses a 20 percent TRU, 80 percent uranium metal fuel clad with HT-9 stainless steel. A summary of plant specifications is provided in Table 8.

Table 8: ABTR Design Parameters. Adapted from (Chang 2006)

ABTR Design Parameters	
Reactor Parameters	**Reference Value**
Electricity Output	95 MWe
Plant Efficiency	38%
Reactor Vessel	Pool
Primary Sodium Temp	355 ºC / 510 ºC
Power Conversion	Supercritical CO_2 Brayton
Fuel Type	metal (~20% TRU, 80% U)
Cladding and Duct Material	Advanced ferritic steel
Burn-up	~115 GWd/t
Conversion Ratio	~0.6
Cycle Length	4 months

There are numerous objectives of the ABTR design, including demonstration of reactor-based transmutation of trans-uranics as part of an advanced fuel cycle, qualification of the trans-uranic-containing fuels and advanced structural materials needed for a full-scale ABR, and supporting the research, development and demonstration required for certification of an ABR standard design by the U.S. Nuclear Regulatory Commission. ABTR designers also have the following objectives:

- To incorporate and demonstrate innovative design concepts and features that may lead to significant improvements in cost, safety, efficiency, reliability, or other favorable characteristics that could promote public acceptance and future private sector investment in advanced breeder reactors;
- To demonstrate improved technologies for safeguards and security;
- To support development of the U.S. infrastructure for design, fabrication and construction, testing and deployment of systems, structures and components for the ABR.

3.2 Potential Causes of Sodium Leaks

Numerous engineered safety features and safety procedures have been built into the next generation of sodium-cooled reactors to reduce the likelihood and consequence of sodium release and fire. These features are extensions of the fire "defense in depth" concepts built into the current generation of nuclear reactors. These fire defenses include (Nowlen 2001):

- administrative programs (to reduce the likelihood and potential severity of fires)
- detection and suppression systems and programs (to rapidly extinguish any fires that might occur)
- separation of safe shutdown equipment trains (to reduce the potential effects of a fire on key plant systems) and
- operating procedures and training (to deal with potential fire-induced losses)

The use of these defenses has led to an excellent record of fire safety at nuclear power plants, particularly in the United States. To date, there have been no fire-induced core damage accidents in the history of commercial nuclear power. However, the unique challenges associated with sodium-cooled reactors may increase the risk of fire at these plants. These risks primarily exist during three stages of a reactor's lifetime; startup, day-to-day operation, and refueling and maintenance. As the nature of the risks varies at each stage, they will be examined individually.

3.2.1 Reactor Startup

Reactor startup is often the most risky time at a NPP, particularly when the startup is of a new reactor design. Great care is taken to start a new reactor in a systematic fashion. The core is loaded and tested at zero power. Primary and secondary flow systems are tested at zero power. Finally, the full system is operated at increasing power levels to ensure it is working properly. A component may not have been tested at 100% operating conditions until these first full-power tests at startup. If a design flaw is present, such as in the Monju example described above, then sodium release may occur.

Even if a component has been properly designed, manufacturing defects could result in sodium leaks (the so-called "infant mortality" failures). Welds, particularly welds of dissimilar metals, represent a potential failure point at startup, and great care is taken to ensure their integrity prior to operation. A poor weld caused a leak on a newly-installed cold trap on the primary circuit of the Russian BR-5/10 reactor (Poplavsky 2004). A micro-crack formed in the weld after the component was heated by sodium. A design defect of a valve in the same reactor caused the valve to lose its integrity when the sodium experienced thermal expansion during startup (Poplavsky 2004). Design defects can also lead to flow blockages within piping or the core region.

As the reactor is operated, the sodium in the primary system will become radioactive. Sodium-24 ($t_{1/2}$=15 hours) is generated from naturally-occurring sodium-23 capturing neutrons in the core region. The level of radiation in the sodium will approach a constant level after a few days of operation. This induced radioactivity introduces additional complications with released sodium. The location of a primary loop sodium leak may be difficult or impossible for personnel to reach due to the high levels of radiation present. If sodium burns, large quantities of oxide aerosols are released. Radioactive sodium in these emissions poses a significant health hazard to plant workers and fire-fighting personnel. In addition, if the sodium vapor is released to the environment, it could represent a health threat to the general public. Perhaps more importantly, it will certainly create a public outcry and could prevent the restart of the reactor. It is for these reasons that additional care is taken to prevent primary loop sodium leaks. Pool-type reactors are favored by some designers in part because of the reduced amount of exposed primary piping and for their generally lower primary system pressures. Those pipes that are exposed are jacketed with secondary piping and inert atmospheres.

3.2.2 Reactor Operation

The most severe consequences of sodium release occur during reactor operation. Great care must be taken to minimize risk of component failure during operation. The potential causes for sodium leaks detailed in this paper include heat exchanger, pipeline, valve, reactor vessel, and pump failure. Two potential initiators of failure are also examined: corrosion and external events. The final source identified in past experience is human error. This particular factor is addressed below in the context of the other potential failure initiators as appropriate.

Heat exchangers

Heat exchangers and steam generators are perhaps the most vulnerable components in a sodium-cooled reactor design. They are composed of thin-walled sodium boundaries, and, in the case of steam generators, these boundaries separate sodium from water. Heat exchanger boundary failures may be caused by material failures or by an overpressure caused by a large-scale sodium-water reaction (King 1991). It is important to detect small leaks before these large-scale reactions are able to occur. It is also critical to be able to rapidly evacuate sodium and/or water to prevent a small leak from initiating a larger one. Since the heat exchangers are the primary method used to remove heat from the core, it is important to have redundancy built into the heat exchanger design. If one heat exchanger experiences a leak and must be taken offline, the remaining heat exchangers must be able to handle the reactor decay heat.

An approach being implemented in many new designs is the use of double-walled tubes in steam generators (Ichimiya 2007). The use of an inner and outer tube in the steam generator design decreases the chance of sodium-water interaction. Periodic non-intrusive inspections of both tubes are needed minimize the chance of simultaneous failure. While the use of two tubes will decrease the heat transfer efficiency, this effect is minimized by keeping the inner and outer tubes in physical contact.

Pipelines/Valves

Pipelines and valves are also relatively vulnerable components in a sodium coolant system. Although these components often have redundant design features and secondary jackets, particularly in the primary loop, leaks can occur. In fact, the decades of operating experience at Russian reactors have shown pipelines and valves to be the main causes of sodium leaks (Buksah 1997). Pipeline leaks are often due to weld failures and issues associated with temperature gradients or cyclic thermal loading. The leaks of the BN-600 and BR-5/10 reactors described above are typical of these types of failures. Small leaks also occurred during the operation of the Russian BR-5/10 reactor in two valves, one due to the failure of a sealing bellows. In this case, sodium leakage was confined to within the guard gland sealing. Another leak occurred due to a design defect on a newly installed valve, as described above. New reactor designs are aiming to eliminate the threat of pipe leaks, although their ability to truly eliminate pipe leaks might be questioned. The JFSR design includes guard piping around all primary and secondary sodium pipes (Ichimiya 2007). Additionally, the space between the sodium piping and the guard pipes is filled with an inert nitrogen environment to prevent sodium combustion.

Another factor that is to be considered relative to sodium piping is the need to prevent sodium-concrete interactions in the event of a leak. As noted earlier, sodium will react violently if it comes into contact with concrete. In the case of Monju, for example, the walls and floor of the facility are lined with stainless steel in areas of sodium piping in order to prevent direct sodium to concrete interactions in the event of a leak. One factor that might need to be considered in this regard is the height to which the lining is installed and the potential that a pressurized piping leak might create a spray fire exposing wall or ceiling surfaces that might not be lined. The potential for such a scenario would be dependent on the extent of concrete lining employed and system pressures.

Reactor Vessel

A failure of the reactor vessel is considered an unlikely cause of sodium leakage (King 1991). The main reason is that many new reactors use pool-type designs, which rely heavily on the reactor vessel for primary coolant containment and which generally operate at low to near-atmospheric pressures. However, there is some possibility that the reactor vessel will leak. Two concepts are employed in all new reactor designs to mitigate the consequences of sodium leaks. The first is the principle of “leak before break” (LBB). Sodium-cooled reactors generally utilize the following features which facilitate the LBB concept (Kubo 1996):

- Low pressure in primary coolant loop to lessen stress on pressure boundary,
- Use of ductile materials to reduce likelihood of brittle failures, and
- Detection of small sodium leaks

The completion of the third feature—detection of a small sodium leak prior to it becoming large enough to release significant amounts of sodium—is vitally important to the success of the LBB concept. All new reactor designs employ sodium detection to minimize potential leaks. Gas sampling-type leak detectors have also been installed in existing facilities (Kubo 1996).

A second concept used to limit the impact of a large reactor vessel failure is the presence of a guard vessel. This vessel acts to catch sodium in the event of a large reactor vessel failure. Guard vessels are employed in the 4S and ABTR designs. In addition to preventing massive amounts of sodium from being released into the containment building (and likely causing a serious fire), the guard vessel prevents sodium from getting lower than the level of the core. Maintaining sodium coolant cover over the core is vital in order to prevent meltdown due to decay heat. The guard vessel would also keep leaking sodium from coming into contact with the concrete surfaces of the primary containment building.

Sodium Pumps

A sodium pump failure can have serious consequences for the operation of a nuclear reactor. This includes the potential for a direct or indirect sodium leak, which can lead to a sodium fire. Pump seizures (the rapid stoppage of a pump), such as those experienced in the sodium reactor at Indira Gandhi Centre for Atomic Research (IGCAR), could result in pressure or temperature transients leading to a sodium leak (Suresh Kumar 2004). A primary sodium pump in the BOR-60 reactor was replaced due to high vibration (Poplavsky 2004). Studies revealed deformation of the pump shaft. Such conditions could result in a violent failure of a pump, which would generate shrapnel and potentially damage other components. Electromagnetic pumps being investigated for many new reactor designs, which contain no moving parts, would eliminate this threat. However, this technology is relatively new, and may cause different problems. For example, traditional pumps provide added safety by slowing spinning down when they lose power. Electromagnetic pumps shut down almost immediately when power is lost.

Other Event Root Causes

A common cause of leaks in water reactors is corrosion. Since the consequences of sodium leaks are greater than water leaks, it is important to understand the effects of sodium corrosion on cladding and boundary elements. Sodium has been found to be compatible with typical fast reactor structural materials in numerous studies, so long as the sodium is kept free of impurities. Other research has extended the sodium-steel corrosion database out to 100,000 hours with positive results (Yoshida 1995). Studies in the BR-5/10 reactor also showed no significant corrosion of material after 40 years of operation with purified sodium coolant (Poplavsky 2004). Similar experience was also seen with the EBR-II reactor in Idaho (King 1999). Based on these results, the use of cold traps to remove oxygen and other impurities from the sodium is vital to the long-term performance of the plant.

External events, such as earthquakes, represent a serious threat in their ability to cause sodium leaks in many of the systems described above. Although most new reactors incorporate seismic isolators into their design, a violent earthquake can still cause severe damage. Of particular importance is the susceptibility of redundant systems to the same external event. For example, if an external event is disruptive enough to shear a pipe in containment, it will likely also rupture the jacketing around the pipe. In this case, the engineered safety systems will need to control the potential fire and maintain core cooling. The potential risk significance of seismic-induced fires for light water reactors has generally been judged to be low (Nowlen, Najafi, *et al.* 2005). However, as noted above seismic-induced piping leaks for a light-water reactor would not present a fire threat. In contrast, a sodium leak resulting from a seismic event would likely result in a fire. Hence, a re-examination of the potential risk significance of seismic-induced fires for metal cooled reactors would be appropriate.

3.2.3 Refueling/Maintenance

Due to their infrequent and hectic nature, refueling and maintenance outages can be a particularly challenging time for sodium fire safety. The complex nature of the refueling procedure coupled with the inability to see through the sodium coolant also creates unique challenges. For example, the refueling process must take fuel rods from the sodium environment with the reactor core, process them through a cleaning process to remove all of the sodium coolant, and ultimately transfer the fuel to a non-inert environment for further handling or processing. One step in such cleaning processes typically involves washing with kerosene. If a sodium fire were to occur during the refueling process, the consequences could be significant. A typical fuel handling system in a sodium fast reactor consists of one or more rotating plugs that provide fuel handling machines access to all fuel assemblies. This type of fuel handling system has led to problems in several reactors.

The BN-600 reactor has had two incidents where faults with the rotating plug system caused damage to the components being loaded into the core (Buksha 1997). Both incidents occurred due to failure of the plug rotation control system, coupled with operator error. A seizure of a rotating plug in the BN-600 reactor was found to have resulted from 15 kg of sodium leaking into the bearing unit (Poplavsky 2004). During an in-pile transfer operation at the India FBTR, an incident occurred that caused damage to the fuel handling gripper, a fuel subassembly, the guide tube, and several reflector subassemblies (Suresh Kumar 2004). This incident was caused by system deficiencies combined with human error. Modifications were made to correct the deficiencies and operation began after two years of downtime.

Sodium loop maintenance has directly caused a number of sodium leaks. The Almeria fire described in Section 2.3 was caused by the improper repair of a leaky sodium valve. A pipe was burst in the BN-5/10 reactor due to an improper sodium re-heating sequence (Poplavsky 2004). Similar actions led to four leaks at the BN-600 reactor. Leaks were also caused when pipes were drained, cut for a repair procedure, and then erroneously re-supplied with sodium. All of these leaks were immediately detected, and corrective actions quickly followed.

Almost all of the maintenance and refueling incidents described in this section resulted from improper (or non-existent) procedures or poor design. In every case, corrective actions were taken to prevent similar incidents from occurring again. Modern versions of rotating plug systems have proven more reliable. Although many leaks of various causes occurred at reactors like the BN-5/10, almost all of them happened during the early stages of the facility operation

(Poplavsky 2004). Learning from the mistakes made in the early days of sodium reactor technology has been vital for the design of new reactors. This experience also highlights the potential importance of human errors as a root cause for sodium fires.

3.3 Sodium Fire Consequences

Sodium fires at any facility can cause serious problems beyond the immediate burn area. However, a sodium fire at a nuclear reactor can have consequences beyond those possible at non-nuclear facilities. This section will address some of the potential consequences of a sodium fire at a nuclear power plant, including the impacts of smoke in the control room, core voiding, reactor undercooling, loss of heat sink, and loss of engineered safety systems.

3.3.1 Control Room

During several non-sodium reactor fires, smoke has entered the control room as a result of fires elsewhere in the plant. In a few of these cases, the smoke affected the operators' ability to react to the situation (Nowlen 2001). At Beloyarsk, a fire started in the turbine building and propagated into the control building, generating smoke in the control room that was so heavy it adversely affected the operators. Reports from the fire at Calvert Cliffs cite smoke in the main control room as one factor that contributed to the operator error, which led to an overcooling transient. During a fire at Narora, smoke rapidly entered the main control room through the ventilation system. The operators had to leave the main control room about 10 minutes into the accident and were not able to re-enter for about 13 hours. The location of the control room relative to sodium-containing areas, ventilation intake locations, and ventilation strategy will need to be carefully considered to prevent such events in the proposed sodium reactors discussed earlier in this chapter.

3.3.2 Core Voiding

A fundamental difference between water and sodium-cooled reactors is the void reactivity coefficient. If the water around the core is voided (boiled, drained) in a water-cooled (thermal) reactor during operation, the power level will automatically drop. The reactor is therefore said to have a negative void reactivity coefficient. In contrast, if sodium is voided in certain sodium-cooled fast reactors (particularly large reactors), it will cause the power level of the reactor to rapidly increase. This reactor is said to have a positive void reactivity coefficient. When the reactor power increases, it can lead to additional boiling and voiding until fuel melts. This positive feedback can lead to extremely rapid surges in reactor power, potentially damaging or melting fuel and cladding.

Multiple events can lead to core voiding during operation, and great care is taken in the proposed new reactors to ensure that these events are prevented. They include sodium boiling, loss of coolant accidents (LOCA), and gas bubble entrainment within the sodium. Sodium fires could lead to sodium boiling if an undercooling event is initiated without scram (reactor shutdown). A severe leak in the secondary system, perhaps coupled with cable fires could lead to this situation. A large leak in the primary system could also disrupt flow enough to induce sodium boiling in the core. A sodium leak in the primary system could also lead to either a LOCA or gas bubble entrainment event. A large primary leak could potentially uncover a portion of the core. If gas is pulled back into a leak in the primary system, the resulting bubbles could also reach the core.

3.3.3 Loss of Heat Sink

A loss of heat sink event can be triggered by sodium leaks in the steam generators. As stated above, the standard procedure in response to these leaks is to drain one or both sides of the steam generator. In the event that multiple steam generators are compromised, reactor cooling must be accomplished with backup safety systems. In the case of the new generation of reactors, these safety systems are generally passive in nature (i.e. they require no operator intervention). These systems ultimately rely on natural circulation driven by core decay heat, and so are also independent of cable fires or loss of site power. In addition to these engineered safety features, the inherent high heat capacity of the sodium and structural elements of the reactor will provide valuable time for operators to restore the system to normal.

3.3.4 Loss of Engineered Safety Systems

The inherent mobility of a fire can cause a fire to become a threat to an entire reactor system. Numerous examples exist of cable fires causing serious problems in a nuclear power plant. Perhaps the most famous of these is the 1975 Browns Ferry fire, where all of the normal core-cooling functions were lost due to a cable fire (Nowlen 2001). However, operators were able to maintain core cooling with a control rod drive pump not included in plant procedures. The fire at Greifswald burned for about 92 minutes causing a station blackout and the loss of all active means of cooling the core (Nowlen 2001). As a result, a pressurizer relief valve opened and failed to close. This situation persisted for at least five hours and led to depletion of the secondary and primary side coolant inventories. The plant was ultimately recovered through initiation of low pressure pumps, the recovery of off-site power, and the recovery of one auxiliary feedwater pump.

These and other incidents demonstrate the need for next-generation sodium-cooled reactors to consider the potential impact of fire on safety systems to maintain core cooling, including the passive safety systems. Every adverse situation cannot be anticipated or avoided. However, if the reactor safety systems operate independent of the plant operators and electrical systems, then these systems can likely maintain cooling until plant personnel put out fires and regain control of the situation.

There is one additional factor that is unique to metal fires that may need to be addressed. Conventional (i.e., non-metal) fires are not generally considered a threat to primary plant piping components used in a light-water reactor (Nowlen, Najafi, *et al.* 2005). This would include the primary piping itself and other piping equipment such as large valves, check valves, and water-filled vessels (e.g., storage tanks). However, sodium fires burn at much higher temperatures than do other types of fires. Hence, metal fires could represent a threat to components and equipment not normally considered fire-vulnerable. For metal-cooled reactors, the performance of plant safety systems and equipment under fire conditions, including the passive safety systems, should be evaluated in this context.

3.4 Summary

Of all the new reactor designs proposed in the Generation IV program, sodium fast reactors have the largest experience base. Thanks in large part to this experience, numerous engineered safety features and safety procedures have been built into the next generation of sodium-cooled reactors. These features are designed to reduce the likelihood and consequence of sodium release and fire.

The risk of sodium release and fire exist during the three stages of a reactor lifetime; startup, day-to-day operation, and refueling and maintenance. Based on past experience, design and manufacturing defects have generated the greatest risk of sodium leakage and fire at reactor startup. Pipes, welds, and steam generator tubes are the most likely components to fail during routine operation. Thermal and mechanical fatigue must be avoided to minimize the chance of these failures. Refueling and maintenance accidents are generally caused by a combination of improper procedures and human error. The experience gained in existing reactors should help to minimize the chance of these leaks.

Sodium fires at any facility can cause serious problems beyond the immediate burn area. However, a sodium fire at a nuclear reactor can have consequences beyond those possible at non-nuclear facilities. The most notable consequences of sodium fire at a nuclear power plant include smoke in the control room, core voiding, reactor under-cooling, loss of heat sink, and loss of engineered safety systems. Sodium fires burn much hotter than other types of fires and might therefore threaten plant equipment, such as piping elements that are not normally considered vulnerable to fire damage. Utilizing past experience to develop suitable safety systems and procedures will minimize the chance of sodium leaks and the associated consequences in the next generation of sodium-cooled reactors. However, some unique considerations do come into play with sodium fires.

4. SODIUM COMBUSTION AND BURNING CHARACTERISTICS

Early research done by Newman in 1972 introduces the topic of liquid metal hazards in normal atmospheres of oxygen and water. One of the main findings through the literature is the significant work done on how metals ignite and burn. However, there has not been as much done on the chemical reaction taking place in the flame zone. To start with the overall sodium combustion and burning characteristics, below in Table 9 are some values of ignition temperatures that Newman reports in his work. There is a large range of ignition temperatures for sodium presented here; this could be caused by different definitions of what "ignition temperature" means. In fact, the concept of an ignition temperature is a misleading one since the critical condition is properly characterized with a Damkohler number, the ratio of the rate of heat release to the rate of thermal dissipation (or some similar definition). When thermal dissipation is fast, any heat released is dissipated and a thermal runaway cannot occur. Makino (2006) has recognized this fact and developed ignition criteria for both droplets and pools that explain at least some of the variation in the ignition temperatures.

There are two distinct forms of metal combustion. One occurs if the metals are less volatile than their oxides in which case combustion is limited to the surface. The second form occurs if the oxide is less volatile than the metal in which case the flame temperature can reach a level where the vapor pressure will move the reaction zone off the metal surface. The boiling point of sodium is 1153 K and the principal oxide is Na_2O with a boiling temperature of 2223 K so the vapour phase mechanism is expected for sodium metal burning (Newman, 1972). However, in many circumstances heat losses are substantial enough that surface oxidation is observed even for sodium; this is particularly true for pool fires (Newman 1972).

Table 9: Sodium Ignition Temperatures Presented by Newman, 1972

Conditions	Ignition Temperature (K)	Source
Droplets, wet and dry air	393	Cowan and Vickers, 1954
Droplets, dry oxygen/nitrogen	473	Richard et al., 1969
Spray, dry air	623-698	Krolikowski et al. (a), 1969
Pool, dry oxygen	482	Lemarchand, 1935
Pool, dry oxygen	433	Cornec and Sannier, 1967
Pool, dry oxygen, at varying pressures	488 (1atm)	Malet et al., 1970
Pool, varying oxygen and water content	733-505	Longton, 1957 (a)
Pool, varying oxygen and hydrogen content	543-515	Longston, 1957 (b)
Pool, atmospheric conditions unspecified	473-323	Morewitz et al., 1967

There are two distinct mechanisms for metal burning as follows (Newman 1972).

- Vapor phase burning takes place above the metal surface, where the metal atoms diffuse outward and the oxygen diffuses inward. This mechanism limits the flame temperature to the boiling point of the oxides produced.
- Surface burning usually takes place with volatile oxides like zirconium where oxygen diffuses to the metal surface and the reaction takes place.

The report written by Newman in 1983 explains the burning process of sodium very well:

> "During the flameless combustion there is a rapid surface oxidation process with the formation of a grey purple product close to the sodium surface and sodium monoxide and sodium peroxide overlaying this layer marked by yellow and white regions. The surface thickness rapidly grows and wrinkles, with oxide nodules or pillars growing in random positions. At pool temperatures in the region of 350-450 °C small flames marked by light and smoke emissions appear on the nodules as vapour phase combustion commences. The oxide pillars act as wicks allowing the liquid sodium within them to be heated above the temperature of the bulk sodium beneath the wick. The nodules appear to commence at regions of the surface where this is a yellow coloration marking the accumulation of sodium peroxide. This surface combustion phase proceeds by oxygen diffusing to the metal surface through porous oxides. The outer oxide layer then becomes remote from the metal, and further oxidation to sodium peroxide reactions (ii) occurs. If at a later stage liquid sodium begins to wet the oxide above it and moves upwards by capillary action it will react with the peroxide releasing heat by reaction (xi)(Newman and Smith, 1973) ."

There is little information about the surface combustion taking place within the sodium air flames. This is because a separation cannot be made between the vapor phase and surface reactions occurring simultaneously. Again, the difficulty associated with the formation of a non-homogenous surface layer with the oxide wick structure is not well understood (Newman 1983).

4.1 Sodium Aerosol Formation

This chapter explains experimental work done in the Beschreibung der Forschungsanlage zur Untersuchung nuklearer Aerosole, (FAUNA) facility in Germany as well as comparative computer codes for sodium aerosol formation. The majority of the experimental work presented here for sodium aerosol formation was carried out by Cherdron, Jordan, and coworkers. The sodium aerosol research would benefit greatly from more R&D.

4.1.1 Experimental Work

Sodium oxide and sodium peroxide are the main products when sodium burns in a normal atmosphere. The products that remain airborne are mainly sodium peroxide; the peroxide reduces to oxide when it makes contact with the metallic sodium surface. These oxides react with the water vapor in the atmosphere to form sodium hydroxide. This all depends on the diffusion of the water vapor to the oxides. Quoting from (Cherdron & Jordan 1988):

> "On the basis of the Fuchs-Sutukin theory the transformation time of 0.1-10 μm sodium peroxyde particles to sodium hydroxyde at relative humidities higher than 35% is faster than 1/10 second (Table 4). At relative humidities higher than 35% the reaction products (NaOH) are droplets. At relative humidities lower than 35% the particles are solid."

The hydroxides then react with the carbon dioxide in the air and form sodium carbonate relatively quickly in a normal atmosphere (Cherdron & Jordan 1988). About 50% of the sodium that went airborne is converted to carbonate after only 1 minute. It was shown that after 260 seconds, with relative humidity greater than 50%, almost all of the airborne sodium was converted to sodium carbonate. In contrast, with relative humidity less than 10%, only 20% of the airborne sodium was converted to carbonate (Cherdron & Jordan 1984). This is similar to what Cherdron & Jordan mentioned in 1988 where measurements showed that this transformation at relative humidities greater than 50% happened faster by a factor of 5 compared to relative humidities at about 5% (Cherdron & Jordan 1988). It was also mentioned that sodium hydroxide particles convert faster to sodium carbonate relative to their size; that is, smaller particles convert faster than larger particles (Cherdron & Jordan 1984).

At relative humidity less than 20% the aerodynamic mass median diameter for sodium fire aerosols in the combustion zone were about 1 μm and for relative humidity greater than 50% the aerodynamic mass medium diameter was measured at about 2 μm (Cherdron & Jordan 1984). For sodium spray fires, it is hard to specify an aerosol formation rate. If the spray is setup properly, 100% aerosol formation can happen. In contrast, a compact spray will have a small aerosol release rate. For almost all the tests, about 30 to 90% of the mass of the sodium was converted to aerosol (Cherdron & Jordan 1988). The remaining oxides are likely carried with the spray and deposited on surfaces. This is a wide range, and the work presented in 1984 by Cherdron & Jordan falls in the same range. Cherdron & Jordan's work in 1988 presented the aerodynamic mass median diameter measured at 1.2 to 1.9 μm. The particles that were measured inside a closed containment experiment were primarily sodium peroxide (Cherdron & Jordan 1988).

In 1988, a five-country consortia studied the evaporation process for sodium aerosols in a fire. The relationship between the sodium burning rate and the aerosol production rate is significantly different depending on the magnitude of the air convective movement. For anything but a sodium pool fire (sodium spray, column, or combined fire), it is suggested that the aerosol production rate is equal to the combustion rate. The differences in aerosol formation are greatly affected by the relative humidity (Jordan *et al.* 1988). The information provided here for aerosol formation is brief but emphasizes some important findings specific to sodium. Most of these experiments were relatively small-scale which could pose a problem for large-scale extrapolation due to scaling effects.

4.2 Sodium Spray Fires

This section covers the sodium spray fire experimental work as well as some computer code development done for sodium spray fires.

4.2.1 Experiments

One of the main groups of large-scale sodium spray fire experiments was performed at the FAUNA facility in Germany. The objective of these experiments was to look at the containment pressure rise with a hypothetical core disruptive accident (HCDA) resulting in a sodium spray into an oxygen-containing atmosphere. Overall the total pressure did not go above 1.8 bars with a spray of 60 kg of sodium that was released in 1.5 seconds (Cherdron & Charpenel 1985a).

The FAUNA test vessel is 6 m in diameter and 6 m tall, having a total volume of 220 m^3. To summarize the experiments performed, all had 20.8 vol.% of oxygen, the sodium temperature was 773 K, and the sodium ejection speed was 20 m/s. The average pressure rise for all experiments was about 0.57 bar/s. There was a lot of uncertainty with the wall temperatures because the thermocouples were simply glued to the surface. The aerodynamic mass medium diameters measured were 1.3 μm and 2.15 μm for the experiments using 7 kg and 20 kg of sodium respectively. For the 40 kg test, the measured diameter was 4.8 μm after 2 minutes. The highest recorded temperature was about 1200 °C (Cherdron & Charpenel 1985a). Table 10 lists the experimental conditions for tests FS1 through FS6 done at the FAUNA facility. This table of information is taken from Cherdron & Charpnel's first report in 1985. Table 11 is the summary of the initial experimental conditions presented for these experiments. Table 12 is a summary of the oxygen consumption for the experiments (Cherdron & Charpenel 1985a).

Table 10: Cherdron & Charpenel, 1985, FAUNA FS1-FS6 Comparison of Experimental Conditions

	Reactor HCDA	FAUNA Experiment	Up Scale
Volume (m^3)	6500	220	1/30
Flow rate (kg/s)	up to 2300	56	1/40
Ejection time (s)	1	0.12-1.0	1
Mass ejected (kg)	up to 2300	7-60	1/40
Ejection speed (m/s)	5-40	20	1
O_2 concentration (vol%)	21	21	1
Sodium temperature (°C)	500-600	500	1

Table 11: Cherdron & Charpenel, 1985, FAUNA FS1-FS6 Initial Experimental Conditions

Experiment	Initial pressure (10^5 Pa)	Initial gas temperature (K)	Nitrogen (% vol)	Water vapor (%vol)	Initial wall temperature (K)	Ejection time (s)
FS1	0.998	296	77.7	1.6	291	0.12
FS2	1.008	297	77.1	2.1	286	0.36
FS3	0.978	272	78.6	1.8	270	0.53
FS4	1.004	273	78.7	0.5	272	0.53
FS5	0.977	279	78.8	0.4	279	0.71
FS6	0.999	287	78.4	0.8	287	1.0

Table 12: Cherdron & Charpenel, 1985, FAUNA FS1-FS6 Oxygen Consumption Results

Experiment	Oxygen concentration after experiment (Vol%)	Total amount of gas (moles) final	Oxygen (moles) final	Oxygen consumed (moles)	Sodium burnt (kg)	Ratio of sodium burnt /sodium ejected
FS1	20.05	8943	1714	86	3.96	0.56
FS2	18.3	8773	1623	277	12.74	0.64
FS3	17.6	8677	1527	373	17.15	0.57
FS4	17.2	8635	1485	414	19.08	0.64
FS5	13.4	8256	1106	794	36.5	0.91
FS6	12.2	8144	994	906	41.7	0.70

Morewitz *et al.* presented experiments of single droplet burning as well as spray fires for sodium. The spray fire experiments are discussed here. These were done in a pressure vessel that was modified to handle high temperatures. Morewitz *et al.* describes the experimental set up as: "a regulated argon gas drive pressure system injected liquid sodium into a fog nozzle where high pressure oxygen atomized the sodium jet and initiated burning to produce high-temperature, high-concentration sodium oxide aerosols." Aerosol samples were measured between 100 and 200 μm in diameter immediately after the spray ended. The impactors collected aerosols that were measured having a diameter between 2 and 4 μm at time 30 seconds after the end of the spray. The large aerosol agglomerates fall out which lead to the reduction in aerosol mass. Below in Table 13 is a summary of the 8 experiments based on the information taken directly from the report (Morewitz *et al.* 1977).

Table 13: Morewitz *et al.*, 1977, High Temperature-Concentration Aerosol Test Summary

Observation	Test							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Mass of Sodium Injected(g)	36	36	67	136	163	215	199	194
Sodium Injection Temperature (°C)	540	539	543	545	540	544	547	550
Injection Time (s)	0.9	0.9	1.6	8.7	8.9	6.8	4.9	5.4
Maximum Pressure Rise (atm)	0.41	0.41	0.61	0.68	0.61	0.80	1.05	0.98
Maximum Gas Tempperature Mid-Vessel (°C)	463	405	990	1045	1010	950	910	1180
Maximum Gas Temperature-Lower-Vessel (°C)	390	20	30	>1200	>1200	210	40	100
Calculated Initial Aerosol Concentration (g/m^3)	110	110	290	560	673	888	822	801
Maximum Aerosol Concentration Measured (g/m^3)	80	-	20	110	270	80	160	80
First Sample at Time (min)	0.1	-	4	0.1	0.1	1	0.3	1

At an International Atomic Energy Agency International Working Group Fast Reactors, Specialists' Meeting, Sodium Fires in 1988, Himeno *et al.* presented leak tests that were performed at the Safety Phenomenology Tests on Sodium Leak, Fire and Aerosols, (SAPFIRE) facility in Japan, with 2.4 tons of sodium that was heated to 505 °C with a flow rate of 3.1 kg/s for 13 minutes. The videos and pictures showed that the flow was a downward column pattern with no ignition. There were rebound droplets from the floor that ignited. About 4% of the sodium burned during the test compared to other spray tests that have shown 30% of the sodium burned in the test. There was an examination done after the test and it "revealed no failure of the jackets and no burning of the thermal insulator around the pipe" (Himeno *et al.* 1988).

A prototype mitigation system was mounted in SOLFA-1[1]. For these tests 3 tons of sodium was heated to 505 °C then spilled from the pipe for 15 minutes at a rate of 3.2 kg/s. The test lasted for 6.6 hours and the oxygen concentrations were maintained around 21% by feeding oxygen into the room or by ventilation. The upper and lower cell aerosol concentration was determined at a maximum of 23 g/m^3 and 5 g/m^3 respectively. The experiments showed that "the combustion rate due to the mixed fires (rebound droplets and pool) was from 100 to 130 kW/m^2 of floor liner that is only 1.1 to 1.3 times larger than that of a pool fire (100 kW/m^2)." The combustion rate in the smothering tank decreased significantly (50 kW/m^2 to 5 kW/m^2) after tens of minutes because of the quick consumption of the oxygen in the tank (Himeno *et al.* 1988).

Tests were also performed to see how the integrity of the structural concrete would hold-up during a sodium leak accident. The tests used gas burners to heat the steel lining. A thermocouple that was at a depth of 500 mm never got above 80 °C during the test. The steel liner was heated to about 500 °C to represent the previous test temperatures. Steam that was released from the heating of the concrete was vented, but the effects of the steam on increasing the sodium fire energy released was not taken into account. There were also tests done to see if the aerosol deposition in the pipes would affect the heat exchanger and electrical instrumentation. There were no significant findings that would prove to pose a threat to the electrical instrumentation. There was a relationship found between the heat transfer coefficient and the average weight of the aerosols; that is, as the weight increased the heat transfer coefficient decreased (Himeno *et al.* 1988).

Malet *et al.* presented a small amount of information about sodium spray experiments. There were nine sodium spray fire experiments in a 3.7 m^3 vessel that involved sodium at 550 °C. The flow rate was varied from 0.4 to 1.5 kg/s, the injection time varied from 1 to 3.5 seconds, and the amount of sodium used was between 0.4 and 5.25 kg for these experiments. There was not much detail in terms of the analysis for these experiments that could be related to the conclusion that the "average atmosphere temperature measurements have a large uncertainty due to the large temperature gradient inside the vessel". Because of the large temperature gradient, convective movement played a large role in the spray fire combustion phenomena. In this vessel sodium has not been shown to "burn more than the molar ratio 3.3 and the maximum over-pressure reached is 2.6 bars" (Malet *et al.* 1981).

4.2.2 Model Development

The second part of the Cherdron and Charpenel study in 1985 compared the computer code PULSAR to the FUANA experiments. PULSAR[1] is a "bidimensional code designed to calculate the thermodynamic consequences and the release of aerosols from burning sprayed sodium in confined atmosphere". The code predicts the overall pressure rise well, but the burning rate is under predicted. There is a need to imporve the oxygen consumption model in order to improve the overall predictive capability. The PULSAR code's droplet combustion model is "described using the Spalding theory connected to the d^2 law for computing the variations in the droplet radii" which brings up another limitation with sodium spray combustion models (Cherdron & Charpenel 1985b). The limitation here is the exclusion of the radiative heat transfer between droplets. That is, these models do not treat radiative heat exchange between droplets which would act to increase combustion rates and completeness.

Krolikowski presents a mathematical model for pressure driven sodium spray fires based on a single (non-interacting) spherical droplet of sodium reacting in air. Krolikowski's report presents the results of pressure driven sodium spray experiments that were performed along with a mathematical model that was developed for a single spherical sodium particle. These experiments measured the pressure rise in the closed reaction chamber. Ten grams of liquid sodium between the temperatures of 350 and 425 °C were injected into the chamber. The pressure in which it was driven in through the nozzle ranged from 1000-1500 psig. The pressure rise rates were measured between 25 and 75 atm/sec with measured pressures of 1.6 to 4.1 atm. The reaction rate was drastically affected by the size of the spray particle, while the spray velocity had a moderate affect. There was a small effect on the reaction rate with respect to oxygen concentrations (Krolikowski 1968).

CONTAIN-LMR is a subcomponent of CONTAIN, a tool that provides integral level analysis of potential accidents in nuclear reactors (Murato *et al.* 1993 and Scholtyssek & Murata 1993). CONTAIN-LMR has models to describe sodium pool fires and sodium spray fires. The sodium spray fire capabilities in CONTAIN-LMR are based largely on the NACOM code developed at Brookhaven National Laboratory by Tsai (Tsai 1980) and it is further described in Scholtyssek & Murata 1993. The model prescribes a fixed burning rate which ignores any droplet heating.

Of primary importance for accident consequences is the formation of aerosols, and CONTAIN-LMR has the ability to model both water and sodium aerosols in some situations. Murato *et al.* does indicate that this multi-species condensation is limited to situations where the two materials are not simultaneously condensing (1983). Since water and sodium-related species condense at very different temperatures, this is not a tremendous problem, but this author can foresee problems if the condensation of radioactive metals/oxides and their interaction with the sodium aerosol are of concern. CONTAIN-LMR also has models to describe the interactions of sodium with concrete, including the out-gassing of vapors from concrete.

4.2.3 Summary

The experimental work presented above included reports from Cherdron and Charpenel, Morewitz *et al.*, Himeno *et al.*, and Malet *et al.*. Cherdron and Charpenel's work discussed the experiments done in the FAUNA facility and the objective of those experiments was to evaluate the pressure rise in the vessel. The pressure did not go above 1.8 bars and the maximum recorded temperature was 1200 °C (Cherdron & Charpenel 1985a). Morewitz *et al.* work consisted of both single droplet and spray experiments for liquid sodium. The spray fires were discussed and Table 13 shows the results. The initial sodium temperatures for the experiments were relatively the same (539-550 °C), while the injection time and sodium amount varied between experiments. There was a noticeable variation in the vessel temperatures and aerosol concentration results (Morewitz *et al.* 1977). Himeno *et al.* presented experiments performed in the SAPFIRE facility that looked into the breach of the vessel's steel liner and electrical equipment failure. These were larger test using between 2.4 and 3 tons of liquid sodium (Himeno *et al.* 1988).

Most of the identified experiments were performed at least 20-25 years ago. Because of the age of the tests the boundary and initial conditions were not well specified, and in particular, are not sufficiently well defined to support the development of the state-of-the-art computer modeling codes. The data collected from these experiments is very useful when comparing with the new experimental data. Inter-droplet interaction in a spray is very difficult to understand. There has been a lot of work done for single droplet combustion, but an unaddressed need for an understanding of how droplets interact with each other during the combustion process for spray fire phenomenon.

With respect to the work presented on the sodium spray fire computer models, it was difficult to completely understand what the models could actually do without access to the user's manuals. The user's manuals were difficult to find in the literature, although efforts to obtain documentation of these models will continue. More research into these models is needed to benchmark the addition of sodium fire expertise into the current fire modeling codes.

4.3 Sodium Pool Fires

This section covers the sodium pool fire experimental work as well as some code development done for sodium spray fires.

4.3.1 Experiments

Below in Table 14 are the conditions of the FAUNA pool fire experiments that were presented by Cherdron and Jordan (1988). This is the same FAUNA test facility in Germany that was described in the sodium spray fire section above.

Table 14: Cherdron & Jordan, 1988, Conditions of the FAUNA Pool Fire Experiments

	F1	F2	F3	F4	F5	F6	F7
Pool suface (m^2)	2	2	12	12	2	5	2
Amount of sodium (kg)	150	250	500	500	350	350	120
Oxygen vol.%	19-22	17-25	15-25	18-25	12-21	4-21	2
Burning pan, heated, isolated	Yes	Yes	Yes	No	No	No	Yes

There were pool fire experiments with up to 500 kg of sodium, 12 m^2 pool area, and a sodium inlet temperature of 500°C. Cherdron and Jordan identify three phases of pool fires described that are "typical for large (e.g. 12 m^2) pool areas":

1. Initial: strong heating of the surround gas which led to about 90% of the maximum gas temperature.
2. Middle: constant temperatures where the height depends on both the pool size and the volume of the vessel.
3. End: the hot residuals are cooling down.

The average burning rate for these experiments was between 20 and 40 $kgNa/m^2h$. For other fires, the typical burning rate is on average 27 $kgNa/m^2h$. For test number 7, there was no visible reaction but there was a strong aerosol release from the sodium pool which corresponded to decreasing temperatures.

There were also combined fire experiments done in the FAUNA facility. These were used to simulate an accident of a sodium leak inside insulation. The understanding is that the sodium would fill the insulation and then cause the shield to break. The sodium release would not be an overpressure spray release. The release of sodium from the FAUNA facility was simulated as follows: 6 m above the burning pan (12 m^2 in area) a sodium outlet was installed (capable 800 gNa/s of flow ejection), the flow rates varied between experiments (range of 50 up to 710 gNa/s), and the maximum amount of released sodium was 810 kg. From these experiments it was shown that the temperature of the gas is "directly connected" to the flow rate of sodium. "For flow rates up to 300 g/sec the temperatures fall immediately; no influence of a sodium pool can be seen." This means that most of the sodium was consumed while in the air so a pool wasn't formed. With higher flow rates, a sodium pool forms and at the end of the injection of sodium an average gas temperature of 300 °C was maintained. (Cherdron & Freudenstien 1988).

Johnson *et al.* describes some sodium pool fire tests done in the 1960's. The experimental setup is described as a vessel 10 ft (~3 m) in diameter and 21 ft (6.4 m) in height. Oxygen concentrations were measured and from these the burning rate was calculated. It was shown that for the 25 lb (11.3 kg) test about 90% of the sodium in the pool was consumed after 20 minutes. Temperature profiles were measured at different radial distances. The radiant heat flux was only measured at one spot 10 ft (~3m) above the pool. There was a lot of uncertainty with this measurement; therefore no radiation correlations were done. There were also a lot of visual observations using a video camera. It was noted that this was an initial effort to understand some fundamental concepts of sodium pool burning. These experiments were broken into stages as follows (Johnson *et al.* 1968):

- Test time (-25 seconds): the sodium was released into the spill pan at 950°F (510°C). There was some smoke noticed when the sodium came in contact with the pan as well as small parts of the sodium had partial ignition.
- Test time (0 seconds): All 25 lbs (11.3 kg) of sodium in the spill pan and there was still small partial burning.
- Test time (+30 seconds): Almost the entire sodium surface was burning. The burning rate and the sodium oxide release rate increased significantly during this time.
- Test time (+60 seconds): The fire was encompassing the entire pool area and the fire was more powerful. The fire was difficult to see, which mean that the oxide production rate increased. The turbulence that was caused by "gas convective currents, had been well established during this period".
- Test time (+90 seconds): The fire was in the full burning phase and the density of the oxide particles increased enough to have almost the entire fire obscured.

The pool fire experiments referenced by Malet *et al.* were done in a vessel at three different facilities varying the volume (4, 2, and 400 m^3). The boundary conditions are not well defined in these experiments. This is a recurring issue with older experimental data. These experiments looked at how the combustion rate was affected by the variations in sodium temperature and combustion area. The initial temperature of the sodium did not show a significant affect on the mean combustion rate. As the combustion area increased, the time averaged combustion rate seemed to decrease. The amount of aerosolized sodium did not exceed 45% of the total burned mass and 52% of the burned mass is in peroxide form (Malet *et al.* 1981).

It was also observed that the thickness of the pool did not have an affect on the combustion rate. When the thickness "exceeds 26.5 cm, the burned mass depends almost solely on the combustion area". That is, the tests showed that the burn rate was dependent on the exposed surface area but not the pool depth. Humidity was shown to inhibit combustion up to a relative humidity of 30% at a temperature of 20°C. This effect slowly disappears above a relative humidity of 60%. At a 12% oxygen molar fraction the surface and vapor phase combustion rates will be similar (Malet *et al.* 1981).

Newman (1982) reports experimental work on small sodium pool fires in different types of atmospheres (i.e. by varying the CO_2 levels) to see if CO_2 had an effect on extinguishment. The experiments used pools between 10 and 30 cm in diameter and up to 15 cm in depth. Table 15 is a summary of the observed burning rate with respect to the different experiments. These experiments showed that extinction can occur with the right amount of inert gas; the complication is designing for the right pool size in an accident scenario in order to obtain the right concentrations. These experiments are small scale, so the issue of extrapolating to a much larger scale still exists (Newman 1982).

Table 15: Newman, 1982, Summary of Results for Sodium Reaction with CO_2

Gas	Observation
Burning in air, sodium pool at 450°C followed by:	
25% CO_2/air	Little reduction in burning rate
50% CO_2/air	Little reduction in burning rate
66% CO_2/air	Extinction after 5 minutes
75% CO_2/air	Extinction after 3 minutes
100% CO_2	Extinction after 2.5 minutes
20% CO_2/argon	Extinction achieved > 5 minutes

4.3.2 Model Development

The purpose of this section is to give a brief overview of some of the models that were developed for sodium pool fires. Ohno talks about the development of the SOLFAS[1] code and presents some sodium experimental results that were used. The SOLFAS code is a three-dimensional code that consists of the fundamental conservation equations. There are other models in the code which include the sodium pool combustion model and heat transfer models. The pool combustion model uses a flame sheet model over the entire pool. The "flame sheet combustion is controlled by sodium and oxygen supplies by diffusion from the pool surface and turbulent mass transfer from the atmospheric gas, respectively". The turbulence model in the SOFAS code was validated against the experimental data from Tropea. The SOFAS code has "the capability to predict the natural convective heat transfer in the region up to $Re=10^{12}$" (Ohno 1990).

Sodium pool fire experiments performed in the FRAT-1[1] vessel in the SAPFIRE facility were referenced in Ohno's report. These experiments were performed to determine the combustion rate of the sodium, which was calculated from the measured oxygen consumption in the vessel. These experiments used 10 kg of sodium that ranged in temperatures between 175 °C to 400 °C. The pool had a depth of 0.2 m of sodium with a cover gas of 3 m^3 and a 3% oxygen concentration. The experimental results were compared to the SOFIRE-MII[1] code. The combustion rate was impacted by the sodium temperature in the experiments. The computation code, however, estimates the combustion rate as a constant. An overview of some sodium column fire experiments were also presented. These tests showed that there are three main factors that affect the columnar combustion rate; the oxygen concentration, the sodium leak flow rate, and the collision velocity of sodium leakage. At the time Ohno's report was written the SOFAS code was still undergoing more development (Ohno 1990).

The SOFIRE-MII, ASSCOPS[1], and SPM[1] sodium pool combustion codes are described in a paper by Miyake *et al.* (1991). All three models were validated against large-scale experiments that were performed in Japan at the SAPFIRE facility and at Kernforschungzentrum Karlsruhe (KfK) in the FAUNA facility. The SOFIRE-MII and ASSCOPS codes have the conventional combustion models in them; that is, where the combustion happens at the pool surface. The SPM model uses a flame combustion model that is more sophisticated. Miyake *et al.* claim that no other sodium combustion codes have been validated against large-scale experiments. The specifics of these combustion models for the three codes are described in some detail. The results of the validation effort showed that all three codes can predict the overall combustion process “reasonably well”. Although SPM has a more sophisticated combustion model, this validation effort did not reveal the difference in the overall combustion process predictions (Miyake *et al.* 1991).

CONTAIN-LMR is a subcomponent of CONTAIN, a tool that provides integral level analysis of potential accidents in nuclear reactors (Murato *et al.* 1993 and Scholtyssek & Murata 1993). CONTAIN-LMR has models to describe sodium pool fires and sodium spray fires. The sodium pool fire model is taken from SOFIRE II (Beiriger 1973). The sodium-concrete interactions are based upon the SLAM model (Suo-Anttila 1983).

4.3.3 Summary

The experimental work presented above for sodium pool fires was a compilation of the research done by Cherdron and Jordan, Johnson *et al.*, Malet *et al.*, and Newman. These works appear to represent a bulk of the early sodium fire experimental research. Cherdron and Jordan presented both sodium pool fires and sodium combined fires performed in the FAUNA facility. The average burning rate was recorded between 20-40 $kgNa/m^2h$. One important observation is that the pool fire test with an oxygen concentration of 2% volume showed no visible reaction but a strong aerosol production was noticed. Johnson *et al.* presented sodium pool fire experiments with a lot of visual observation data. There was an experiment with 25 lbs of sodium that was 90% consumed in 20 minutes. However, there was trouble with the heat flux measurements. Malet *et al.* presented experiments for sodium pool fires that had similar results to that of the sodium spray fire experiments. The maximum amount of aerosolized sodium was 45% of the initial sodium mass and 52% of the burnt sodium was in the peroxide form. One of the differences was Malet *et al.* noted that the thickness of the pool did not have an effect on the combustion rate. Again, a lot of the experimental work did not record the boundary conditions well enough for the state-of-the-art fire modeling that is being developed today. These experiments will be used for comparison with new experiments

With respect to the work presented on the sodium pool fire computer models, it was difficult to completely understand what the models could do without access to the user’s manuals. The user’s manuals were difficult to find in the literature, although efforts to obtain these documents will continue. More research into these models is needed to benchmark the addition of sodium fire expertise into the current fire modeling codes.

5. CONCLUDING REMARKS

This report documents the results of the initial stage of the “Metal Fire Implications for Advanced Reactors” Laboratory Directed Research and Development project. Efforts to date have included an extensive literature search to cover the sodium fire recorded accidents, the proposed LMFBR designs and safety concerns and sodium fire combustion experiments and research.

Past experiences/accidents with sodium fires at nuclear and non-nuclear sodium facilities were investigated to identify the types of hazards that must be accounted for when designing the next generation of sodium-cooled nuclear reactors. The risk of sodium release and fire exists primarily during the three stages of a reactor lifetime; startup, day-to-day operation, and refueling and maintenance. Utilizing past experience to develop suitable safety systems and procedures will minimize the chance of sodium leaks and the associated consequences in the next generation of sodium-cooled reactors.

A need also exists to improve the state-of-the-art fire modeling codes to include the sodium fire combustion phenomenon. The past experiments did not record the details of the boundary conditions for both pool and spray fire scenarios. A lot of the experiments were small scale compared to the amount of sodium that could be involved in a HCDA. There exists a need to understand the phenomenon of inter-droplet interactions in a spray fire scenario. There has not been any experimental work to address this. Fire is one of the key parameters in a NPP risk analysis. With the GNEP program making progress forward, expertise in metal fires is essential for Sandia National Laboratories.

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7. APPENDIX A: ANNOTATED BIBLIOGRAPHY

Berte, M. *et al*, 2007, *Radioactive Sodium Waste Treatment and Conditioning: Review of Main Aspects*, IAEA-TECDOC-1534. International Atomic Energy Agency, Vienna, Austria.

This paper provides a comprehensive review of the hazards associated with sodium waste management. Roughly half of the document focuses on sodium waste generating, handling, and treatment processes. This includes draining sodium and NaK from plant systems; in situ treatment of residual sodium; cutting techniques for pumps, valves, piping and other components; cleaning of components; potential reuse of sodium; and removal of selected radionuclides from sodium waste with the objective of reducing the waste classification or converting it to exempt waste. The review includes both successes, failures, and failure analysis. Throughout the publication, emphasis is placed on industry experience and application of sodium and NaK. This paper is especially useful in identifying the potential hazards and hazard mitigation considerations.

Buksah, Y.K., *et al*, 1997, Operation Experience of the BN-600 Fast Reactor, in *Nuclear Engineering and Design*, vol. 173, p. 67-79

This paper discusses the operating experience of the BN-600 power plant, which has operated since 1980 in Russia. The BN-600 is a pool-type 600 MW_e reactor with oxide fuel. The bulk of the paper discusses details of the reactor system performance and operational experience. There is also a good discussion of abnormal events, including sodium leaks. Over its operational lifetime, the plant experienced numerous sodium leaks and associated fires. These leaks predominantly occurred in the early years of reactor operation. The main causes of sodium leaks at this plant are pipelines, valves, flange joints, and human error. It was found that manufacturing defects and design faults were the primary root cause of the component failures.

Chang, Y.I., P.J. Finck, and C. Grandy, 2006, Advanced Burner Test Reactor Preconceptual Design Report, ANL-ABR-1 (ANL-AFCI-173). Argonne National Laboratory, Argonne, IL.

The Advanced Breeder Test Reactor (ABTR), developed by ANL, is a sodium-cooled, pool-type reactor based on experience gained from the EBR-II reactor. It is a 95 MW_e design with an estimated 38 percent plant efficiency. It has such low power because it was developed as a test bed for a similar commercial design-the Advanced Breeder Reactor. This paper provides very detailed engineering descriptions of plant components and systems and contains numerous diagrams of these components. These systems include the reactor core, sodium heat exchangers, power conversion, fuel handling, and instrumentation. It also has an evaluation of the safety design criteria for the reactor.

Cherdron, W. & S. Jordan, 1982, *Physical and Chemical Characterization of Sodium Fire Aerosols. Kernforschungszentrum Karlsruhe*, Laboratorium fur Aerosolphsik und Filtertechnik, 7500 Karlsruhe, West Germany (pp 77-79).

This paper is one of several that describe the pool and spray fire tests done in the FAUNA facility. The only difference here is that the results were used to see how well the code PARDISEKO is with calculating aerosol behavior. “The PARDISEKO code calculates accurate the course of the aerosol mass concentration using an instantaneous source of a definite initial aerosol concentration” within a containment vessel. This paper points out the importance of a better understanding of aerosol behavior for pool fires. This paper identifies things that seem simple that can possibly have a drastic effect on the aerosol behavior; including the relative humidity, turbulent convection, chemical composition, and other ambient environmental issues not accounted for.

Cherdron, W., Dr. S. Jordan, & W. Lindner, 1984, *Sodium Fire Particles-Chemical Transformation and Properties. Liquid Metal Engineering and Technology*, Proceedings of the Third International Conference held in Oxford on 9-13 April 1984 (Vol 2: 287-290).

This report again also references the tests that were done in the FAUNA facility. There is more investigation on the aerosol aerodynamic mass median diameter and how it is affected by relative humidity. At relative humidity less than 20%, the aerodynamic mass median diameter for sodium fire aerosols in the combustion zone were about 1 μm and for relative humidity greater than 50% the aerodynamic mass medium diameter was measured to be about 2 μm. These experiments also have “shown that sodium fire aerosols convert relatively fast from sodium hydroxide to sodium carbonate in normal atmospheres”. About 50% of the sodium that went airborne is converted to carbonate after only 1 minute. “The conversion rate depends strongly on the relative humidity.” It was shown that after 260 seconds, with relative humidity greater than 50% almost the entire airborne sodium was converted to sodium carbonate. On the contrary with relative humidity less than 10%, only 20% of the airborne sodium was converted to carbonate. It was also mentioned that sodium hydroxide particles convert faster to sodium carbonate relative to their size; that is, the smaller particles convert faster than larger particles.

Cherdron, W. & J. Charpenel, 1985a, *Thermodynamic Consequences of Sodium Spray Fires in Closed Containments, Part 1-Experiments*. Laboratorium für Aerosolphysik und Filtertechnik, Kernforschungszentrum, Karlsruhe.

This report presents large-scale sodium spray fire experiments performed at the FAUNA facility. The objective of these experiments was to look at the containment pressure rise with a core disruptive accident resulting in a sodium spray into an oxygen-containing atmosphere. Overall, the total pressure did not go above 1.8 bars with a spray of 60kg of sodium in only 1.5 seconds. A lot of the heat was assumed to be absorbed by the walls in the experiments due to the large uncertainties in the results. There is a lot of experimental data presented in this report in the forms of tables and graphs. This will be a good report to compare new experimental data with.

Cherdron, W. & J. Charpenel, 1985b, *Thermodynamic Consequences of Sodium Spray Fires in Closed Containments, Part 2-Calculations with PULSAR*. Laboratorium für Aerosolphysik und Filtertechnik, Kernforschungszentrum, Karlsruhe.

This report is the second of two parts for this work with the FAUNA experiments. Here the computer code PULSAR is compared to the experiments. PULSAR is a "bidimensional code designed to calculate the thermodynamic consequences and the release of aerosols from burning sprayed sodium in confined atmosphere". The code predicts the overall pressure rise well, but the burning rate is under predicted. There is a need for improvement in the oxygen-consumption model. The PULSAR code's droplet combustion model is "described using the Spalding theory connected to the d^2 law for computing the variations in the droplet radii" which brings up another limitation with sodium spray combustion models.

Cherdron, W., 1986, *Experimental Results of Large-Scale Sodium Spray Fires. Science And Technology of Fast Reactor Safety*. BNES, London, 75-77.

Experiments performed in containment at the FAUNA Facility are presented here. These experiments replicated a small leak with a pressure release of sodium creating a spray pattern. The results were temperature and pressure rise over time graphs. The flow rate, amount of sodium and nozzles were varied in the experiments. There was no capture of the energy or heat release rate of the sodium. The maximum pressure increase that was observed was 2 bar. Peak temperatures were observed to exceed 900°C but there was a concern noted that the local gas temperature could be dependent on height. It was noted it took about 300 seconds to get an averaged value for temperature in the vessel. They also collected data on the sodium concentration in air and found that there was a "fast decrease of the mass concentration which reaches less than 10 gr Na/m^3 after 11 minutes. It has been found, that the aerosol consists of nearly 100% sodium-peroxide".

Cherdron, W. & S. Jordan, 1988, *Aerosol Release from Sodium Fires and their Consequences for Reactor Components*. International Atomic Energy Agency International Working Group Fast Reactors, Specialists' Meeting, Sodium Fires. Obninsk, USSR, June 6-9, pp 44-56. Report Numbers XA0201146-1171, IWGFR/67.

Here there are experiments presented that were performed the FAUNA facilities that were discussed in the "Sodium Fire Research Programs for SNR Safety in the FRG" also written by Cherdron. There was some data on the aerodynamic mass median diameter of the sodium fire particles for both open-to-atmosphere and closed-containment fires. It was shown that the particles measured only a few mm above the pool fire flame zone were only slightly different from the particles measured a few meters above the pool fire.

Cherdron, W. & K Freudenstien, 1988, *Sodium Fire Research Programs for SNR Safety in the FRG*. International Atomic Energy Agency International Working Group Fast Reactors, Specialists' Meeting, Sodium Fires. Obninsk, USSR, June 6-9, pp 38-42. Report Numbers XA0201148-1171.

This paper describes a sodium fire research program called KfK at the Nuclear Research Center is Karlsruhe, Germany. There were pool fire experiments with “pool areas up to $12m^2$ and up to 500kg of sodium with a sodium inlet temperature of 500°C”. There were also combined fire experiments that were done in the FAUNA facility. It was used to simulate an accident of a sodium leak inside insulation. The understanding is that the sodium would fill the insulation and then cause the shield to break so the sodium release would not be an overpressure-spray release. Sodium spray fires were also performed in the FAUNA vessel to simulate a leakage in a sodium pipe. As mentioned previously sodium in a normal atmosphere will ignite and cause a fast temperature and pressure increase. The computer code PARDISEKO IV was developed for aerosol behavior. This code predicts the evolution of the “polydisperse aerosol system in a closed containment” and “a deposition process by natural turbulent convection”. There is also mention of the INTERATOM Gmbh , NABRAND code that was developed for a sodium leak fires.

Gluekler, E.L. & T.C. Huang , 1979, *Response of Secondary Containment to Presence of Sodium and Hydrogen*. Nuclear Engineering and Design, North-Holland Publishing Company (55:283-291).

This paper addresses issues that are “expected to present a major challenge to containment integrity”. These are “short-term pressurization by sodium spray or pool fires following energetic ejection on sodium into the containment” and “long-term pressurization by sodium vapor and hydrogen after failure of the reactor vessel and guard tank”. This paper describes in some detail a postulated low-probability core disruptive accident. The computer codes SOFIRE and CACECO are introduced for the evaluating the hydrogen generation rates. The codes SRAY and SOMIX are introduced for evaluating sodium spray fires inside the containment building and its consequences. The paper focuses on the hydrogen production and buildup from a release of liquid sodium. The lower flammability limit of hydrogen with air is as low as 4%. Limiting the amount of hydrogen buildup would be useful to avoid the potential of a hydrogen explosion inside containment. This research showed that a hydrogen explosion does not “follow energetic events because of the early oxygen depletion by sodium fires”. In the event of a melt-through “hydrogen recombination in the containment following sodium jet ignition, may not deplete the oxygen rapidly enough”. It is recommended that purging the containment atmosphere could avoid this.

Heisler, M. & H.A. Morewitz, 1979, *An Investigation of Containment Pressurization by Spray Fires*. Nuclear Engineering and Design (55:219-224).

This study took a hypothetical core disruptive accident (HCDA) and looked at how it would affect the secondary containment structure. The SOMIX-1 sodium spray fire code was used in this study. For light metal fast breeder reactors the HCDA for this case is “produced by arbitrarily inserting unrealistically large amounts of reactivity in a short period of time…..in principle, generate a large bubble of vaporized fuel, cladding, and coolant which can then cause the upper sodium pool to impact at high velocity on the bottom of the reactor vessel head and thereby damage the seals and loosen the plugs so that the pool sodium, followed by the contents of the HCDA bubble, can vent into the secondary containment atmosphere”. A hydraulic analysis was done for two different pressure scenarios of gas bubbles, the first case was a 20 atm pressure rise that decayed to 2 atm in 10 seconds and the second case was a 5 atm pressure rise that decayed to 2 atm in 10 seconds time. From this, 6 atm was calculated to be the maximum pressure rise assuming all the oxygen was consumed in the containment building. This calculation is based on work by Humphreys. It is not practical for all of the oxygen in the containment to be consumed, so the actual pressure rise is going to be lower than the maximum calculated pressure rise. The overall physical dynamics of how the spray fire works in relation to the different temperature layers is discussed. The hot gases are going to rise and the sodium will fall to the lower part of containment, which means there is going to be some type of cooling effect with a sodium spray fire scenario.

Himeno, Y. *et al*., 1988, *Development and Demonstration of Sodium Fire Mitigation System in the SAPFIRE Facility*. International Atomic Energy Agency International Working Group Fast Reactors, Specialists' Meeting, Sodium Fires. Obninsk, USSR, June 6-9, pp 135-148. Report Numbers XA0201155.

Leak tests were performed in the SAPFIRE Facility with 2.4 tons of Na that was heated to 505C with a flow rate of 3.1kg/s for 13 minutes. The cameras and pictures showed that the flow was more of a downward column pattern with no ignition. There were rebound droplets from the floor that ignited. About 4% of the sodium burnt during the test compared to other spray tests that have shown 30% of the sodium burnt in the test. There was examination done after the test and it "revealed no failure of the jackets and no burning of the thermal insulator around the pipe". The combustion rate for both the open pool and the smothering tank with an opening of ratio of 1% were determined. The combustion rate for the smothering tank with an opening ratio of 1% was only about 3% of the combustion rate for the open pool.

There were tests to see how the integrity of the structural concrete would hold-up during a sodium leak accident. The tests used gas burners to heat the steel lining. The thermocouple that was at a depth of 500 mm never got above 80C during the test. The steel liner was heated to about 500C to represent the previous test temperatures. Steam that was released from the heating of the concrete was vented, but the effects of the steam on increasing a sodium fire energy released was not taken into account. There were also tests done to see if the aerosol deposition in the pipes would affect the heat exchanger and electrical instrumentation. There were no significant findings that would prove to pose a threat to the electrical instrumentation. There was a relationship found between the heat transfer coefficient and the average weight of the aerosols, as the weight increased the heat transfer coefficient decreases. The figure referenced for this has six data points and a curved fit to it.

Ichimiya, M., T. Mizuno, and S. Kotake, 2007, A Next Generation Sodium-Cooled Fast Reactor Concept and its R&D Program, in *Nuclear Engineering and Technology*, vol. 39, no. 3, p. 171-186.

The Japan Atomic Energy Agency (JAEA) Sodium Fast Reactor (JSFR) is a sodium-cooled, advanced loop-type reactor evolved from Japanese fast reactor technologies. It is a 1500 MW_e design with an estimated 42 percent plant efficiency. The JSFR design uses a trans-uranic, mixed oxide (TRU-MOX) fuel with a fast spectrum flux to achieve breakeven burn-up. The paper provides a brief overview of the design with some good diagrams and detailed plant specification tables. Three primary areas are being improved upon with this design. The first is the reduction of construction cost. The second is an improvement in core performance characteristics such as the breeding capability, actinide burning characteristics, fuel burn-up, and operation cycle length. The third target area for improvement is sodium safety. It is concluded that the engineered safety features overcome the inherent danger of working with sodium in this design.

Johnson, R.P. *et al*., 1968, *Characterization of Sodium Pool Fires*. Proceedings of the International Conference on Sodium Technology and Large Fast Reactor Design, Part I, Sessions on Sodium Technology, Argonne National Laboratory, ANL-7520, pp. 195-205.

This paper provides a description of the state of knowledge in 1968. There are descriptions of the basic physics and limiting processes in sodium pool fires. The authors identify three primary things that the burning rate depends on. These are the "rate of oxygen arrival to the burning region", "rate of reaction of oxygen with sodium", and "diffusion of sodium vapor through the oxide layer to the burning region". The authors then go into describe the four regions for a simple sodium pool fire. They are trying to prove that the heat balance for a simple model is somewhat of a difficult task. There are also suggestions for further research including variations in the spill areas, sodium temperature, and oxygen concentration that were the subjects of subsequent studies in the 70's and 80's.

Jordan, S. *et al*, 1988, *Sodium Aerosol Behavior in Liquid-Metal Fast Breeder Reactor Containments*. Nuclear Technology, (81:183-192).

This was a group effort with five countries involved to study the evaporation process of sodium oxides in a fire. In a contained space, about 40% of the burnt sodium in aerosolized in a pool fire. The relationship between the sodium burning rate and the aerosol production rate is significantly different depending on the magnitude of the air convective movement. For anything but a sodium pool fire (sodium spray, column, or combined fire) it is suggested that the "aerosol production rate by combustion is equal to the combustion rate". The aerosol mass mean diameter (AMMD) for sodium pool fire is seen to increase rapidly because of the high concentrations (0.5 μm to 1 μm). It decreases after several hours. The table in the report (Table II), "EMIS Experiment Variation of Aerosol Production Rate," that shows how the production rate of aerosols varies with different stages of sodium combustion for a pool fire provides important data. This report again mentions the difficulties with environmental effects on sodium combustion and the differences in aerosol formation being greatly effect by the relative humidity.

King, R.W., 1999, *Considerations for Advanced Reactor Design Based on EBR-II Experience*, ANL/ED/CP-99117. Argonne National Laboratory-West, Idaho Falls, ID, October 1999.

EBR-II, a pool-type, sodium-cooled reactor and power plant, operated for thirty years (beginning in 1964) as a proof-of concept demonstration plant, a fuels and materials test and irradiation facility, and an operational test bed for liquid-metal reactor components. It also served as an operational safety transient testing facility, and finally as a prototype for the Integral Fast Reactor program. The paper discusses the key features of EBR-II that contributed to its reliability and concludes that many of these features must be incorporated into the next generation of sodium-cooled reactors. It also addresses how cost considerations must play a role in moving forward with sodium reactor development.

King, T.L., R.R. Landry, E.D. Throm, and J.N. Wilson, 1991, Preapplication Safety Evaluation Report for the Sodium Advanced Fast Reactor (SAFR) Liquid-Metal Reactor, NUREG-1369. Nuclear Regulatory Commission, Washington, D.C.

The SAFR reactor was designed in the late 1980s. The standard SAFR design consists of four reactor modules, each with a thermal output of 900 MW_{th}. The core is fueled by a metallic U-Pu-Zr alloy and is cooled by flowing liquid sodium. This report is a preliminary technical evaluation of the safety features generated by the NRC as part of the design review for the reactor. An overview of the reactor and balance of plant designs is included, with emphasis on safety concerns for each component. Accident analyses are provided for design-basis accidents, and additional details of these analyses are provided in the appendices. The paper also includes recommendations for research and development programs required to support the design. Although DOE terminated work on the SAFR design in 1988, this document provides a complete review of the safety features designed up to that time.

Krolikowski, Theresa S., 1968, *Violently Sprayed Sodium-Air Reaction in an Enclosed Volume*, ANL-7472. Argonne National Laboratory, Argonne, Illinois.

This report presents the results of pressure-driven sodium spray experiments that were performed along with a mathematical model that was developed for a single spherical sodium particle. These experiments measured the pressure rise in the closed reaction chamber. Ten grams of liquid sodium between the temperatures of 350 and 425C were injected into the chamber. The pressure in which it was driven in through the nozzle ranged from 1000-1500psig. The pressure rise rates were measured between 25 and 75 atm/sec with measured pressures of 1.6 to 4.1 atm. The reaction rate was drastically affected by the size of the spray particle, while the spray velocity had a moderate effect. There was a small effect on the reaction rate with respect to oxygen concentrations. The mathematical model presented was for a single spherical droplet of sodium through air. The report goes into detail about the derivation and the assumptions put forth for this model.

Kubo, S., Y. Hashiguchi, and A. Okabe, 1996, R&D Needs for Evaluation of Sodium Fire Consequences and Aerosol Behavior for DFBR, in *Technical Committee Meeting on Evaluation of Radioactive Materials Release and Sodium Fires in Fast Reactors*, Ibaraki, Japan, November 11-14, 1996. International Atomic Energy Agency, Vienna, Austria.

This paper discusses the research and development requirements to evaluate consequence and aerosol behavior of sodium fires. It is specifically written to assist in the design of the Japanese Demonstration Fast Breeder Reactor (DFBR). It first discusses general safety principles used to mitigate sodium leaks and reduce the consequences of leaks that do occur. These principles are discussed in detail and include tabulated summaries. Current design concepts for sodium fire prevention are then discussed. These include measures used inside and outside of containment, early detection, and aerosol prevention. Finally, an evaluation of the sodium fire safety of the DFRB design is provided. This evaluation is fairly detailed and includes results from sodium fire models, such as the CONTAIN code developed at SNL.

Leibowitz, L., 1967, *Thermodynamic Equilibria in Sodium-Air Systems*, Journal of Nuclear Materials 23, North-Holland Publishing Co., pp 233-235.

This author took some work done by White, Johnson, and Dantzig and expanded it with a new computer program that tries to minimize free energy. These are pressure calculations for containment in the case of a sodium leak. Varying the atmospheric conditions brought about different results. This report does not introduce new topics for this report, but some of the references can be looked into.

Lhiaubet, G. *et al*, 1990, *Comparison of Aerosol Behavior Codes with Experimental Results from a Sodium Fire in a Containment*. 1990 International Fast Reactor Safety Meeting, Snowbird, UTAH (pp 1-13).

This is a study of a comparison of four codes and how well they predict typical data from aerosol production from experiments done in CEN-Cadarache, France. These experiments were sodium fires in a 400 m^3 vessel that lasted 90 minutes with measurements taken over a 10 hour period. The codes that were compared were PARDISEKO, AEROSIM, CONTAIN, and AEROSOLS/B2. The results of this showed a "discrepancy between calculated and experimental results ranges from a factor of 3.5 to a factor of 20" which can be accounted for by the wall depositions being significantly underestimated by all of the codes.

Lineberry, M.J. and T.R. Allen, 2002, The Sodium-Cooled Fast Reactor (SFR). Americas Nuclear Energy Symposium, Coral Gables, FL, October 16-18, 2002.

The Sodium-Cooled Fast Reactor (SFR) system, developed by the INL for the Generation IV program, features a fast-spectrum, sodium-cooled pool-type reactor. The fuel cycle employs a full actinide recycle with two major options. These options use various fuel types, reactor power levels, and cycle lengths. As this reactor was in the early stages of development, the paper does not provide large amounts of detail regarding the engineering design. However, the general design principles are discussed. The SFR is designed for management of high-level wastes and, in particular, management of plutonium and other actinides. Important safety features of the system include a long thermal response time, a large margin to coolant boiling, a pool-type primary system that operates near atmospheric pressure, and intermediate sodium system between the radioactive sodium in the primary system and the water and steam in the power plant.

Luster, V.P. and K.F. Freudenstein, 1996, Feedback from Practical Experience with Large Sodium Fire Accidents, in *Technical Committee Meeting on Evaluation of Radioactive Materials Release and Sodium Fires in Fast Reactors*, O-aria, Ibaraki, Japan, November 11-14, 1996. International Atomic Energy Agency, Vienna, Austria.

This paper discusses the Almeria and ILONA sodium fire accidents in detail. The Almeria solar plant accident occurred in August 1986 at a test facility near Almeria, Spain. Prior to the accident, the plant was shut down to repair a leaking sodium valve. The valve was to be repaired under a gas pressure of 5.1 bar. An auxiliary seal failed during repair, sending a strong sodium jet into the room and creating a violent sodium spray fire. Several personnel were injured during the event, and the fire was able to propagate to adjacent rooms.

ILONA was a large sodium test facility of natural convection in decay heat removal loops located at Bensberg, Germany (Luster 1996). The facility consists of a tower-shaped building of steel framework construction on a concrete basement. A sodium fire and a severe sodium-concrete interaction occurred in September 1992 at an auxiliary installation in the basement of the ILONA site. The leak initiated when a failure in the pressure regulation valves caused control gas to become unavailable. The increasing gas pressure partially opened a gland plug, causing a slow (~0.2 kg/s) leak of sodium. Sodium continued to leak from the vessel for five hours, ultimately releasing 4300 kg. Spilled sodium came in contact with the concrete floor and walls, initiating a sodium-concrete reaction. The concrete of the floor was lifted by reaction products and the thermal expansion of the reinforcing steel. Subsequent investigation revealed much about the sodium-concrete interaction and the thermal impact of hot reaction gas on unprotected concrete.

Makino, Atsushi, *2006 Ignition Delay and Limit of Ignitability for Sodium Pool (Theory and Experimental Comparisons)*." JSME International Journal, Series B, Vol. 49, No. 1.

This study focuses on the parameters that affect the ignition delay of a sodium pool based on the premise that ignition prevention is the ultimate goal. Makino has identified parameters through the application of perturbation theory that if they remain controlled, it will make igniting a sodium pool more difficult. Along with a dependence on temperatures, oxidizer concentration and heat losses, the study pointed out that ignition is inhibited with reduced surface-to-volume ratio for the pool; that is, a pool that is thermally massive relative to the available surface area will be more difficult to heat further. The model is successful at predicting ignition criteria for several different sodium pool data sets, including several from the Japanese language literature.

Makino, Atsushi, *2005 Ignition and Combustion of a Falling, Single Sodium droplet*." Proc. Combust. Instut., Vol. 31, pp 20747—2054.

This paper presents experimental measurements for sodium droplet ignition along with a model for ignition based on activation-energy asymptotics. The parameters that directly affect the ignition delay for a droplet are the oxygen concentration, the initial speed of the droplet, the initial diameter of a droplet, and the temperature. Model predictions are compared with the experimental data sets and good agreement is indicated.

Malet, J.C. et al., 1981, *Potential Results of Spray and Pool Fires. Nuclear Engineering and Design* , North-Holland Publishing Company (68:195-206).

This paper presents a series of sodium pool ignition and fire experiments and a series of sodium spray fire experiments. For pool fires, results are presented for burning rate dependence on sodium temperature, pool geometry, oxygen concentration and humidity, although the data presented is incomplete from the perspective of being able to define boundary conditions for simulations. Pool fire experimental results were compared with results obtained using the FEUNA code, although the conditions used for the model were not defined. Spray fire measurements were also reported in terms of temperature and oxygen concentrations as a function of time, although the paper indicates that inhomogeneities result in large (unspecified) uncertainties. Spray measurements are compared with the PULSAR code. As before the conditions for the spray fires are not well defined.

Mikami, H., A. Shono, and H. Hiroi, 1996, Sodium Leak at Monju (I)-Cause and Consequences, in *Technical Committee Meeting on Evaluation of Radioactive Materials Release and Sodium Fires in Fast Reactors*, O-aria, Ibaraki, Japan, November 11-14, 1996. International Atomic Energy Agency, Vienna, Austria.

The Monju Prototype Fast Breeder Reactor first reached criticality in 1994. Powered operation was begun in 1995, and a series of power raising tests were performed, with a planned full-power test planned for June 1996. Monju is a loop-type 280 MW_e sodium-cooled reactor with mixed oxide fuel. During a scheduled power rating test (40% electrical power) on December 8, 1995, a leak occurred in a damaged temperature sensor. The paper describes the failure mechanism in detail, discusses the procedure for diagnosing the leak, and details the work done to prevent such an accident from occurring again.

The work done to prevent another accident is discussed in detail. In addition to replacing all similarly designed temperature sensors, aspects of sodium fire response and emergency operation procedures were also modified at the Monju site. This work resulted in the Monju Improvement Plan, which is detailed in the paper. The Monju plant is scheduled to resume operation in mid-2008.

Miyagi, K. & S. Miyahara, *Development of In-Vessel Source Term Analysis Code, TRACER*. Power Reactor and Nuclear Fuel Development Corportation, XA0055534, pp 161-168.

The TRACER code models behavior of fission products through the sodium pool when a postulated fuel breakage occurs. This article does not include information about metal combustion, so in terms of necessary information for understanding metal fires this report might be of use for cited references.

Miyake, Osamu *et al*., 1991, *Sodium Pool Combustion Codes for Evaluation of Fast Breeder Reactor Safety*. Journal of Nuclear Science and Technology, 28[2], pp 107-121.

The SOFIRE-MII, ASSCOPS, and SPM sodium pool combustion codes are described and were validated against large-scale experiments that were performed in Japan at the SAPFIRE facility and in KfK in the FAUNA facility. The SOFIRE-MII and ASSCOPS codes have the conventional combustion models in them, where the combustion happens at the pool surface. The SPM uses a flame combustion model which is more sophisticated. As of when the report was written, the authors claim that no other sodium combustion codes have been validated against large-scale experiments. The specifics of these combustion models for the three codes are described in some detail. The results of the validation effort showed that all three codes can predict the overall combustion process “reasonably well”. Although SPM has a more sophisticated combustion model, this validation effort did not reveal the difference in the overall combustion process predictions.

Newman, R.N., 1972, *The Ignition and Combustion of Sodium-A Review*, Central Electricity Generating Board, Research Department, Berkley Nuclear Laboratories (RDBN2229).

This paper reviews knowledge of sodium combustion and ignition as it stood in 1972. There is particular attention to the properties of surface oxide layers and the role that their coherence plays in inhibiting ignition. To this end Newman discusses the oxide layers that form in different oxidizing environments. The paper points out the importance of surface burning in the combustion process. While vapor phase burning can occur and is expected based on thermodynamic considerations, substantial heat losses present in pool fires commonly lead to surface burning. Newman discusses the thermochemistry of sodium oxidation products and intermediates and also the spectral signatures of sodium combustion. Newman also has a more recent review described below.

Newman, R.N. *et al*., 1973, *Explosive Interactions Between Sodium and Water, and Material Wastage in the Vicinity of Leaks in Sodium Water Heat Exchangers*. Berkeley Nuclear Laboratories. Proceedings of the International Conference, Liquid Alkali Metals, British Nuclear Energy Society, London, England, April 4-6, pp 85-91.

There is a lot of experimental work explained here. The two main areas that are discussed are, the sodium water interactions under certain conditions causing an explosion and the material decomposition that can lead to a leak in a heat exchanger. An explosion can occur with a hot metal and water interaction, the “greater surface area of the assembly of particles over that of the original metal results in a high rate of heat transfer which in turn produces steam explosively”. The concern is corrosion in the heat exchanger when water and sodium interact. From this reaction sodium hydroxide can form and with water vapor at high temperatures, corrosion can occur. This can possibly even happen at micron levels.

Newman, R.N., 1982, *The Role of Carbon Dioxide in the Combustion of Sodium in Air*.

Proceedings of the L.M.F.B.R. Safety Topical Meeting, Central Electricity Generating Board, Ecully, France, Volume III, pp III-3-III-11.

This paper presents experimental work on small sodium pool fires in different atmospheres (varying the CO_2 levels) to identify the role of CO_2 in inhibition. Structures observed on the pool surface that support the oxide layer are identified as containing carbon derived from reactions between sodium and carbon dioxide. This observation is linked to the effectiveness of carbon or graphite based fre suppressants. It is also observed that at certain pool temperatures (above 600 C) the carbon may oxidize and also release additional sodium oxide aerosols. The pool fire experiments were pools the size between 10 cm and 30 cm in diameter and up to 15 cm in depth.

This report is helpful as it describes in detail the physical nature of what was going on during the experiments. Things like surface layer formation and small fires over the pool were discussed. These experiments showed that extinction can occur with the right amount of inert gas, the complication is designing for the right pool size in an accident scenario, in order to obtain the right concentrations. These experiments are small scale, so the issue of extrapolating to a much larger scale still exists.

Newman, R.N., 1983, *The Ignition and Burning Behaviour of Sodium Metal in Air*. Progress in Nuclear Energy, CEGB, Berkeley Nuclear Laboratories, Berkeley, Gloucestershire, U.K.. (12, 2: 119-147).

This paper discusses some physical and thermochemical properties of liquid sodium, relating them to the thermal balance that determines the nature of the combustion process. The knowledge of specific kinetics is also presented. The authors other work, described in the above paragraphs, is also extensively reviewed. In addition to the topics noted above, there are sections on vapor-phase jet flames, spray flames, larger pool fires (both unconfined and confined) and sodium fire suppression techniques. The fact that sodium is chemically reactive with both water and oxygen in the atmosphere is mentioned in many papers including this one. Newman states "most spillage of liquid sodium can be expected to result in a fire" given the temperatures of operation in a reactor. There has been a lot of effort in hydrocarbon fire research. There has been a good amount of sodium fire research but much of it is basic focusing on the burning of sodium with respect to scale. A lot of the effort has focused on developing codes but their predictions were not reviewed specifically. "A major part of this review is a presentation of the large amount of quantitative data on the burning rates of sodium sub-divided according to the physical form of the element…The end objective of the studies described is of course to be able to deal with sodium spillages as a potential large-scale industrial hazard."

There is little information about the surface combustion within the sodium air flames. This is because a separation can not be made between the vapor phase reaction occurring in parallel. Again the issue of the formation non-homogenous surface with the oxide wick structure adds another level of difficulty.

There is talk about the flame height for a sodium jet in the vapor combustion section. There are a couple standard referenced flame height correlations mentioned, but these can only be used for sodium to "quantify the behavior of coherent laminar or turbulent jets of sodium if sodium monoxide is considered as the major product". The next section describes the droplet, sprays, and jet combustion. For these cases the sodium is dispersed into a closed or semi-closed vessel which results in a temperature and pressure rise. There is a lot of reference again to many different experiments that will be followed up on.

Nowlen, S.P., M. Kazarians, and F. Wyant, 2001, *Risk Methods Insights Gained from Fire Incidents,* SAND2001-1676P. Sandia National Laboratories, Albuquerque, NM.

This report presents the findings of an effort to gain new fire PRA methodology insights from fire incidents that have occurred at nuclear power plants. A set of 25 fire incidents at nuclear power plants is analyzed to provide data for the review. These incidents are also summarized in an appendix of the report. The review focuses on two types of actions and events. The first are events that illustrate interesting insights regarding factors that fall within the scope of current fire PRA methods. The second are events observed in actual fire incidents that fall outside the scope of current fire PRA methods. Fire PRA insights are then drawn based on these observations. The paper concludes that the overall structure of a typical fire PRA can appropriately capture the dominant factors involved in a fire incident. However, several areas of potential methodological improvement are identified.

Ohno, S. *et al*., 1990, *Test and Code Development for Evaluation of Sodium Fire Accidents in the FBRs*. International Fast Reactor Safety Meeting, Power Reactor and Nuclear Fuel Development Corporation, Japan, pp 241-250.

This report talks about the development of the SOLFAS code and presents some sodium experimental results that were used. The SOLFAS code is a three-dimensional code that consists of the fundamental conservation equations. Sodium pool fire experiments performed in the FRAT-1 vessel in the SAPFIRE facility were referenced in this report. The experimental results were compared to the SOFIRE-MII code. The combustion rate was shown to be impacted by the sodium temperature in the experiments. The computation code however, estimates the combustion rate as a constant.

An overview of some sodium column fire experiments were also presented. These tests showed that that there are three main factors that affect the columnar combustion rate. These are the oxygen concentration, the sodium leak flow rate, and the collision velocity of sodium leakage. At the time this report was written the SOFAS code was still undergoing more development.

Plys, Martin G., Michael Epstien, & Boro Malinovic, 2000, *Uranium Pyrophoricity Phenomena and Prediction*. Safety Analysis Working Group Workshop 2000, Santa Fe, NM. Fauske & Associates, Inc. SNF-6192-FP.

There have been experiences with uranium pyrophoricity in DOE complexes in the past which have no capture the relevant physics of the phenomenon. The idea of this paper is to compile a report that encompasses the work done on uranium pyrophoricity in order to have an understanding of what research is available. A heat transfer, mathematical model is presented for a piece of metallic fuel. Both natural convection and radiation are considered. There are postulated reaction rate correlations for uranium in different environments. There are some incidents presented with the ignition of uranium. A deterministic approach is suggested here which includes all the potential scenarios where ignition can occur with uranium. This document is more of a procedural document in screening for these types of incidents and how to evaluate them. For the purpose of investigating sodium fire, the only part of this report that is pertinent are the uranium incidents reported.

Poplavsky, V.M. *et al*, 2004, Review of Fast Reactor Operational Experience Gained in the Russian Federation; Approaches to the Co-Ordinated Research Project, in *Operational and Decommissioning Experience with Fast Reactors meeting*, Cadarache, France, March 11-15, 2002. International Atomic Energy Agency, Vienna, Austria.

This paper summarizes the experience with operating sodium-cooled reactors gained in Russia. This experience is largely based on the operation of the BR-5/10, BOR-60, and BN-600 reactors. For each reactor, a basic description of reactor parameters is provided. A summary of the operating experience is then given, with a focus on abnormal events and sodium leak incidents. Causes and consequences of sodium leaks are analyzed, and it is concluded that most problems arose early in the lifetime of each reactor.

The report concludes that the feasibility of sodium-cooled has been demonstrated in all portions of their life-cycle. It further concludes that the operation of the BN-600 in particular demonstrates that advanced sodium-cooled reactors are a viable, cost-effective source of future energy. Finally, it is concluded that safety of these reactors has been demonstrated.

Randich, E. & A.U. Russell, 1983, *Large Scale Exploratory Test of Sodium/Magnetite Concrete Interactions*, SAND83-0356. Sandia National Laboratories, Albuquerque, NM.

This report describes a test series performed at SNL to investigate concrete and sodium interactions. This SAND report evaluates the two magnetite concrete experiments. Experiment number 14 "incorporated a bare magnetite concrete crucible with a cylindrical cavity and a relatively shallow sodium pool (123 kg of sodium). The test was designed to examine the interaction between molten sodium at 82K and unprotected magnetite concrete". The other magnetite concrete experiment was test number 15 which was more complicated than test 14. "The test incorporated a square crucible cavity with a flawed steel liner and sued 243kg of sodium. The purpose was to examine the attack of vertical magnetite concrete walls and insulating siliceous firebrick which were partially protected from the sodium by a steel plate containing flaws".

These experiments showed that an energetic reaction is possible with molten sodium and magnetite concrete. Temperatures as high as 1150K were recorded in the reaction zone. A heat generation rate was calculated at maximum of $1.3x10^5$ J/m^2s and this was lower than what was seen in the limestone concrete experiments. For the unprotected magnetite experiment number 14 all of the sodium was consumed but the experimenters are not certain if the penetration into the floor would have gone further had there been more sodium to interact. The maximum downward penetration was 11cm and the maximum observed penetration rate was 2.5 mm/min. Test experiment number 15 used firebrick which provided no protection for the magnetite concrete. These experiments have shown that the interaction between molten sodium and magnetite concrete need to be considered in the design process because it is significant when the reactions occur. There were no wall penetrations recorded for these experiments.

Randich, E., Smaardyk, J.E. & A.U.Russell, 1983, *Large-Scale Exploratory Tests of Sodium/Limestone Concrete Interactions*, SAND82-2315. Sandia National Laboratories, Albuquerque, NM.

This report evaluates experiments that were performed at SNL under the Advanced Reactor Safety Research Program, looking at the interactions between molten sodium and calcite concrete. The results of 11 tests are presented in this report that took place between 1977-1981. Molten sodium was poured on top of concrete. "The experiments were monitored for gas and aerosol evolution, temperatures in the sodium pool and concrete, and erosion rate of the concrete. The independent variables considered included sodium temperature, sodium pool depth, the effects of sodium hydroxide additions on the interactions, concrete construction methods, and concrete crucible geometry." Any where from 20-200kg of molten sodium that was initially heated between 673 K and 973 K was used.

The conclusions from these experiments were that an energetic reaction can occur with the interaction of limestone concrete and molten sodium. The maximum recorded temperature in the reaction zone was 1173 K but for only for a short time. Heat fluxes were measured from $3x10^4$ to $4x10^5$ J/m^2s. It was also noted that there is a threshold temperature for the sodium where an energetic reaction does not occur, this temperature threshold range is 723 K to 773 K. There was a delay time from when the molten sodium came into contact with the concrete; this could be because of the location of the thermocouple below the concrete surface. The maximum observed delay time was recorded as 30 minutes. As expected, hydrogen was the main gaseous specie produced from these experiments. "A small amount of methane was present if the hydrogen concentration in the cover gas in the test article exceeded a composition of 30% hydrogen." The downward penetration for these experiments were anywhere from 1cm to 15cm. This is comparable to the magnetite concrete experiments where the maximum downward penetration was 11cm. "Ultrasonic techniques indicated penetration rates of from 1 to 4 mm/min for short periods of time." Those are maximum rates and the penetration rates are not steady. Some of the experiments ceased when all the sodium was consumed, while there were others that ceased before all the sodium was consumed. "Only by understanding the mechanism by which penetration is occurring will a predictive capability be obtained for modeling the sodium/concrete interactions in reactor accident situations."

Sakashita, Y., 2004, 4S Current Status. 2004 Alaska Rural Energy Conference, Talkeetna, AK, April 27-29, 2004.

This presentation provides a top-level overview of the Toshiba 4S reactor. The 4S reactor is a fast-spectrum, sodium-cooled pool-type reactor. Designs with power outputs ranging from 10 to 50 MW_e have been proposed. The 4S reactor is intended for use in remote locations and to operate without refueling during its 30-year life. The 4S has been compared with a nuclear "battery" because it does not require refueling. The lack of refueling would mean that the reactor's fuel supply would be a capital cost rather than an operating cost. The presentation also discusses additional potential applications for the 4S reactor, including desalination and hydrogen production.

Suresh Kumar, K.V. et al, 2004, Fast Breeder Test Reactor; 15 Years of Operating Experience, in *Operational and Decommissioning Experience with Fast Reactors meeting*, Cadarache, France, March 11-15, 2002. International Atomic Energy Agency, Vienna, Austria.

This paper overviews the operating experience of the FBTR. The FBTR is a 40 MW_{th} sodium-cooled loop-type reactor located in Kalpakkam, India. It was designed to help the Indians gain experience in the design, construction, and operation of fast reactors and sodium systems. The paper outlines the operating experience for the past 15 years, including issues with refueling, steam generators, sodium leaks, and reactor transients. The paper concludes that the overall system performance has been satisfactory and the experience has provided incentive to move forward with the development of large fast reactors.

Tucek, K., J. Carlsson, and H. Wider, 2006, Comparison of Sodium and Lead-Cooled Fast Reactors Regarding Reactor Physics Aspects, Severe Safety and Economical Issues, in *Nuclear Engineering and Design*, vol. 236, p. 1589-1598.

In this paper, two fast reactor systems are discussed and compared—the sodium-cooled fast reactor and the lead-cooled fast reactor. First, comparative calculations on critical masses, fissile enrichments and burn-up swings of mid-sized SFRs and LFRs (600MWe) are presented. Further, reactivity transient events and decay heat removal failures were analyzed for both systems. The calculations revealed that LFRs have an advantage over SFRs in coping with the investigated severe accident initiators (ULOF, ULOHS,TLOP). This is caused by the greater natural circulation behavior of LFR systems and the much higher boiling temperature of lead. The paper further concludes that the LFR has an economic advantage since it does not require an intermediate coolant circuit. However, it was also proposed to avoid an intermediate coolant circuit in an SFR by using a supercritical CO2 Brayton cycle.

Yoshida, E., S. Kato, and Y. Wada, 1995, Post-Corrosion and Metallurgical Analysis of Sodium Piping Materials Operated for 100,000 Hours, in *Liquid Metal Systems*. Edited by H.U. Borgstedt and G. Frees, Plenum Press, New York, NY

This paper presents corrosion data for steel that has been exposed to sodium for 100,000 hours. In particular, surface corrosion morphology, microstructure, chemical composition, and high-temperature strength were evaluated after long-term exposure to sodium. The paper overviews test procedures and results. It was observed that thermal gradient mass transfer phenomenon seen during short-term tests continue during long-term exposure. The paper concludes that long-term exposure of steel to sodium does not result in significant corrosion levels.

Yuasa, Saburo, 1984, *Spontaneous Ignition of Sodium in Dry and Moist Air Streams*. Twentieth Symposium (International) on Combustion, The Combustion Institute, pp 1869-1876.

This report presents some results of sodium pool burning experiments, but the explanation of the observed burning behavior and phases that sodium went through is more important for a fundamental understanding. Yuasa mentions that there is a wide disparity of ignition temperatures reported for sodium. He thinks it has a lot to do with the actual definition or criteria of the “ignition temperature” and there are a lot of concerns of how the sodium is stored prior to the experiment. The state of the sodium metal before it burns can significantly impact the experimental results.

That whole process was for sodium in a dry air stream, for a moist air stream the observations were similar. The appearance was different though. “At the instant when the sample was exposed to the moist air stream, it was uniformly covered in a white film.” Then soon after the sample’s film layer turned a yellow-greenish color. Similar to transition I for the dry air stream, there were a number of small wrinkles along the surface and a large temperature increase. These wrinkles then turned to a dark green color which was called transition II. The temperature continued to increase and the film turned black and a small flame appeared near the center of the sample. Comparing both the dry and moist air streams there is a HRR plot which doesn’t seem to show much difference between the two.

8. DISTRIBUTION

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