THE SODIUM COOLANT USED IN ASTRID AND OTHER SODIUM FAST REACTORS

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Abstract*—Since the 2000 Generation IV International Forum, there has been tremendous growth in the development of liquid coolants in nuclear reactors [1]. Sodium Fast Reactors (SFRs), such as France's Astrid, use unmoderated neutrons to yield greater energy return than thermal nuclear reactors. This technology requires greater temperature control, a problem solved by using sodium coolant. This paper will analyze the safety and effectiveness of the sodium coolant used in SFRs in an effort to showcase recent progress and the potential for further nuclear development in the modern world.*

Benefits of sodium coolants over gas, lead, and water coolants include optimal pressure and temperature ranges, lower costs, and increased simplicity of design [2]. However, sodium reactions and sodium boiling are two issues that need to be resolved before rectors like Astrid can be commercially operational. In Astrid, high temperature resistant robots, acoustic detectors, and ultrasonic sensors create a safe environment for generating clean energy.

Once officially running, the Astrid, and all future SFRs, will fall in line with the Generation IV restrictions in the areas of sustainability, economic proficiency, safety, anti-proliferation, and peaceful alternative uses [3]. The lowered threat and greater benefit of SFR energy production will prove to be a necessity as the world searches for alternative energy sources that lack greenhouse gas emissions and are able to produce mass quantities of energy.

Key Words—Astrid, Generation IV, Nuclear Energy, Nuclear Reactors, Reactor Safety, Sodium Coolant, Sodium Fast Reactors.

AN OVERVIEW OF GENERATION IV REACTORS

Thermal nuclear reactors have been used around the world since the mid 20th century. The characteristics that define these reactors are neutron moderator coolant, control rods, and the connotation of being unsafe. As nuclear energy research progressed, a new standard of nuclear reactors began to develop and the turn of the century brought the development of sustainable guidelines for modern reactors. These are known as the Generation IV Guidelines.

Generation IV Guidelines

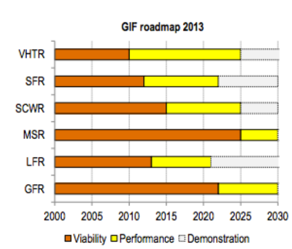
In January of 2000, over one hundred researchers collaborated to create a plan of action for the future of nuclear energy at what is now called the Generation IV International Forum (GIF). In their deliberations, these researchers decided that all modern reactors should meet specific requirements in the areas of sustainability, economics, safety, and proliferation [1].

Prior to the Generation IV initiative, the majority of operable reactors measured a CDF between $2.6x10^{-5}$ and $5x10^{-5}$. CDF stands for core damage frequency and is a measurement of the probability of the reactor core becoming damaged in a given year. In other words, with the number of thermal reactors currently in use, a catastrophic event, such as a meltdown, is estimated to occur approximately every forty to eighty years [4].

As it should, this statistic justifies public fear surrounding nuclear energy and on the surface makes it difficult to ethically support nuclear reactors. Part of the Generation IV sustainability goal, however, is to increase civilian quality of life and lessen the societal burden of unsafe nuclear practices. Even with the current CDF, only two major nuclear accidents in the worldwide cumulative 15,000 years of reactor runtime have had a significant negative impact on those people living around the reactor [5]. In addition to this already low statistic, Generation IV Nuclear Reactors aim to further lower the CDF to $1x10^{-6}$, making it ten times less likely for a reactor meltdown to occur in a given year. This would make nuclear energy significantly safer and more sustainable, providing a higher quality of life for society in the present as well as for future generations [4].

As progress goals are met, the GIF updates the specific outlines for meeting the Generation IV goals, such as increasing core safety and minimizing nuclear waste. The forum also tracks the development of the six types of reactors that are predicted to be viable Generation IV Reactors. Among these reactors, sodium cooled fast reactors (SFRs) lead in areas of development and viability.

FIGURE 1 [6]



A 2013 chart showing progress in different Generation IV reactors

As seen in Figure 1, SFRs are entering their performance period in research and development. This illustrates the political and social support behind these reactors and that they will soon be ready to begin transitioning to commercial use.

Sodium-Cooled Fast Reactors

Within the core of thermal reactors, there are fuel beds of enriched Uranium-238. Rods are periodically inserted into the core in order to absorb neutrons and slow the fission process. This method creates a reaction that can be controlled but limits energy yield and thus has resulted in a total accumulation of 270,000 metrics tons of spent nuclear fuel that is stored in containment vessels worldwide [7]. In the long run, this inefficiency is unacceptable because naturally occurring Uranium-238 is a finite resource that must be conserved if nuclear energy is to be used as a sustainable source of energy. Innovations such as fast reactors have been created to decrease fuel usage and combat waste piles that inhibit nuclear energy from realizing its maximum sustainability potential.

Fast reactors opt not to use the control rod method. Instead, the fast reactors allow the neutrons to remain at high speeds that cause non-fissile material to become fissile [1]. Thus Plutonium-239, Uranium-238, and transuranic isotopes can be consumed within the reactor core and will broaden the scope of nuclear fuel options [3]. This also opens the option of using the current accumulated nuclear waste as modified fuel in the future [6]. This will significantly reduce the volume of stored waste, decreasing the environmental impact. This will also allow transuranic isotopes and other actinides created during the reaction to be consumed as fuel rather than being part of the waste cycle [1]. SFRs therefore have less waste and are more efficient than thermal nuclear reactors. In addition, the lifetime of this waste is much shorter than that of the waste created by thermal reactors. In this way, SFRs promote sustainability through their increased efficiency and ability to improve current environmental conditions.

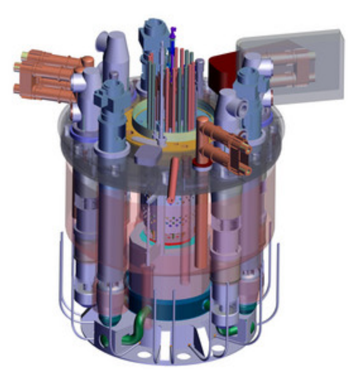
Another advantage of fast reactors is an increase in energy yield. This increase has been estimated to be between factors of 60 to 70 when using natural uranium in SFRs as compared to thermal reactors [1]. This increase in production efficiency comes from the use of unmoderated neutrons and their ability to sustain and produce fission reactions. This is supplemented by a greater ability to consume a large variety of fuels. These two factors alone bring down the costs of producing electricity and therefore have the potential to decrease consumer costs. Following Generation IV guidelines, SFRs decrease capital costs of building nuclear reactors and decrease the risk of costly investment, should problems occur. SFRs are able to achieve this through reduced frequency of fuel reloading, improved in-service inspection and repair, and extended plant lifetime up to sixty years [6]. This will allow nuclear energy to compete with currently affordable energy. Thus, with reduced cost and investment and increased longevity, SFRs are much more economically sustainable than thermal reactors.

The SFRs under Generation IV Guidelines also use passive cooling during power loss to prevent nuclear core destruction in the event of a natural disaster [1]. This lessens the need for off-site emergency response, as specified by the Generation IV guidelines [6]. The effects of core meltdown to the surrounding area would be much less devastating because the reaction would be more controlled. The preventative measures of the SFRs further create an environment where commercial use of nuclear energy is safe. This contributes to the social and environmental sustainability required by Generation IV guidelines and expected by all responsible engineers.

Astrid as an Example of SFR Technology

The push to commercialize SFRs is international. Russia, Japan, and China among several other countries are making efforts to design and commercialize SFRs that meet Generation IV goals. Astrid, an SFR in France, is in its development phase with the expectation to be operational for demonstration by 2020 [8]. The CEA, the French government's nuclear research department, is working with private sector partners to create new innovations for Astrid that optimize efficiency and maximize safety. For reference, Figure 2 illustrates the design of Astrid's core as published by the CEA. Due to the highly anticipated development of this technology, the research surrounding Astrid is often cited when analyzing sodium coolant used in SFRs. Therefore, Astrid serves as a prime example of current innovation in Generation IV SFRs and is useful to keep in mind when analyzing sodium coolant technology.

FIGURE 2 [8]



A diagram of Astrid's core

THE ROLE OF LIQUID COOLANTS

Fast reactors require a coolant in order to control the temperature of the fission reaction and prevent damage to the reactor's core. Decay of the enriched Uranium results in fast neutron bombardment of fuel, raising the temperature in the core. To ensure the temperature stays within a safe range, the core must be in the presence of a coolant. Fast reactors lack control rods, which regulate the speed of neutrons, further increasing the fast reactor's dependence on the coolant. While many different elements and compounds have been considered for the use of coolant in fast reactors, the four main coolants that have been studied extensively are gas, lead, water, and sodium.

Gas as a Potential Coolant

There are many advantages of using a gas, such as argon or helium, as a coolant in fast reactors. These gases are inert and unreactive to most other elements, if not all, because they have a filled outer electron orbital [3]. This advantage ensures that no dangerous reactions occur between the coolant, water, steam, or pipes. The other advantage of a gas coolant is that it is transparent, not opaque like liquid metals, so there is greater ease associated with in-service inspection and repair. The gas will also cause little to no corrosion of the surrounding materials that make up the reactor. However, while extensive research is being conducted on gas coolants, there are drawbacks and complications that prevent them from being used in fast reactors today.

Because gas is very low density, the primary circuit that contains the coolant must be pressurized [3]. This leads to complications in the design and significantly increases the cost of the reactor [8]. One must also note the breeding gain of gas-cooled fast reactors (GFRs). Breeding gain measures the ability of a reactor to consume non-fissile fuel beds. Because the breeding gain of GFRs is slightly negative in the first cycle of the reactor, approximately -0.01, the GFR is anticipated to have more difficulty in utilizing non-fissile fuel blankets [9]. This means that the fuel options are more limited for GFRs than for other types of fast reactors. In addition, the low heat extraction capability of gas coolants requires that the core runs at a power density reduced by a factor of two or three as compared to other fast reactors [3]. As a result, the energy yield of gas reactors is much less than that of other fast reactors, reducing sustainability. While gas reactors have naturally greater safety and less corrosion, lower efficiency, increased costs, and greater complexity of design render them impractical for the time being.

Lead as a Potential Coolant

While lead is less reactive than other coolants, its toxicity, freezing point, and density make it unfavorable for use in fast reactors. Unlike sodium, lead does not react with air or water, which leads to benefits in the design of the lead-cooled fast reactor (LFR). For example, the steam generator of the reactor could be placed within the primary vessel without risk of harmful reactions [9]. This simplicity of design would decrease the cost of running the reactor, allowing LFRs to exceed Generation IV guidelines in the area of economic sustainability.

However, lead is inherently toxic, corrosive, and has an undesirable freezing point. Because of lead's toxicity, the handling of lead coolant in reactors needs to be closely monitored. This makes general maintenance of the reactor difficult and increases risks associated with potential disaster situations [3]. Lead is also highly corrosive which would threaten the structural integrity of the reactor and call for higher amounts of structural maintenance. Thus, a layer of iron oxide would have to be placed on all of the steel surfaces, such as pipes, that come into contact with the coolant. With this oxide layer, the temperature of the reactor must be maintained between 400 and 480 degrees Celsius [9]. This furthers the need for frequent and intense reactor maintenance.

Even though the corrosiveness and toxicity of lead provide significant drawbacks, the largest problem is lead's operational temperature range. The freezing point of lead, 327 degrees Celsius, is close enough to the required temperature range for use as a coolant that there is an increased potential for lead freezing. This could result in lead blockages in the reactor core and inhibit the flow of coolant. Such clogging was seen in a Russian experimental LFR and caused fuel assembly meltdown and significant core damage. Other disadvantages of lead include its opaque appearance, which makes in-service inspection and repair difficult, and its high density, which inhibits coolant flow. Lead's drawbacks and toxicity result in a reduction of environmental sustainability in LFRs, lessening their promise as Generation IV reactors. Despite its benefits, lead is not an ideal coolant for fast reactors [9].

Water as a Potential Coolant

While water coolant is safe in that it has no potential for harmful coolant-steam reactions, its temperature range is not conducive to the speed at which neutrons must move in a fast reactor [3]. Though used in thermal reactors, a study published in January of 2013 found that water is not even considered by researchers for fast reactors due to the difficulty it would impose on energy production. When water is used as a coolant, only enriched uranium can be used as fuel, which limits the reactor's ability to produce energy and lowers economic and environmental sustainability [9]. This undermines the purpose of using a fast reactor and makes water as a potential coolant obsolete.

Sodium as a Potential Coolant

Having considered all other options, sodium is left as the most viable option for a coolant in a fast reactor given its physical properties, efficiency, and time scale. One property of sodium is its operable temperature range, which is approximately 200 to 550 degrees Celsius [8]. This particular temperature range optimizes the fission reaction while still ensuring that the reaction is controlled. Between its melting point and its boiling point, sodium does not activate and does not interact with the neutrons involved in the fission process. Also, the wide temperature range of sodium easily captures the optimal operation range, meaning that sodium is able to operate under a larger variety of radiation and core temperatures. The temperature range also offers leeway to slow the reaction during maintenance without completely shutting down the reactor. Due to the fact that lead's melting point is close to the reactor's operable temperature, lowering the core temperature for maintenance in LFRs would result in blockages. Sodium on the other hand has a melting temperature of 97.72 degrees Celsius, far enough from the temperature range that sodium freezing is of no concern. Sodium's temperature range is optimal for use in fast reactors [9].

In addition, sodium has a relatively high density that allows fast reactors with sodium coolant to operate at atmospheric pressure [3]. This increases the safety of the reactor in potential crisis situations and allows for simpler passive safety measures to be utilized. The simplified design allows the reactor to run at the pressure surrounding the facility, putting less stress on the reactor structure [9]. Also, conducting the reactor at atmospheric pressure makes predicting reactions within the core easier because there is one less variable to consider.

The efficiency of the reactor is also greater when using sodium coolant. The typical SFR's core power density is 207 MW/m^3, very high compared to other types of fast reactors [9]. The core power density measures the amount of energy that is extracted from a certain volume of fuel. Therefore, having a high power density means that more energy can be extracted using less fuel [3]. In addition to having a high power density, SFRs have a breeding gain of zero during their first cycle [9]. This shows that fuel beds with less fissile material are still operable and that a wider variety of fuels can be used in SFRs. The breeding gain also indicates that the SFR is able to yield more energy from the actinides produced during fission because it can extract energy from a wider variety of sources. This increased efficiency reduces costs and maximizes energy production, increasing economic and environmental sustainability.

Sodium is also nontoxic and less corrosive than lead. Because sodium is nontoxic, the recovery from potential crisis situations is much simpler. Furthermore, sodium does not require an iron oxide layer to prevent corrosion to the steel pipes and thus requires less frequent maintenance. In fact, when using stainless steel with pure sodium, there is no corrosion at all [9]. This makes running the reactor much simpler.

Finally, sodium is a cheap coolant because it is abundant. The inexpensive price of sodium allows the reactor as a whole to become economically efficient [9]. One goal of Generation IV reactors is to decrease risk to investment and make nuclear energy a competitive and economically sustainable form of energy production. Sodium's low cost and high efficiency would meet this goal. SFRs have also been subject to a much larger breadth and depth of research than GFRs or LFRs. Thus, SFRs have more mature technology, allowing them to become commercially operable much sooner than other fast reactors. However, there are several problems associated with sodium coolants that must be addressed before SFRs can truly become operable.

RISKS ASSOCIATED WITH SODIUM COOLANTS

When deciding on the coolant for a fast reactor, the coolant must have physical properties that can easily sustain the fission reaction. In addition, the overall cost must be low enough to make energy readily accessible with a competitive price, while the risks associated with production must be easily manageable. Sodium easily satisfies the first two of these qualifications. However, at first glance, risks such as sodium reactions and sodium boiling may seem daunting.

Sodium Reactions

There are two main types of sodium reactions that are of concern in SFRs: reactions with water and reactions with air. Sodium-water reactions are known to be violently exothermic, and thus there is a necessity to prevent them in SFRs. When sodium comes into contact with water, it produces excess sodium hydroxide and hydrogen. Sodium hydroxide, in the form of soda, is highly corrosive and can damage pipes and other metal surfaces in the core. Also, the excess hydrogen can react with the surrounding environment, creating potential for fire and explosion [3]. The sodium's temperature will then increase to the point where the core will be damaged. Under these circumstances, the neutrons would be much more difficult to control and the safety of the reactor would be jeopardized. The uncontrollable nature of this situation makes the elimination of sodium-water contact an essential component of reactor safety. Another reaction that is of concern is the reaction between sodium and air. When sodium is exposed to air, it ignites and has the potential to combust hydrogen. This is a great threat to the reactor and must be avoided [9].

Sodium Boiling

There are various dangers associated with sodium boiling and sodium gas entrapment within SFRs. The void coefficient of reactivity as defined by the United States Nuclear Regulatory Commission is, "a rate of change in the reactivity of the … reactor system resulting from a formation of … bubbles as the power level and temperature increase" [10]. Thus, to ensure a safe reactor environment, a very low or negative coolant void coefficient is desired. However, due to the chemical properties of sodium and core designs, sodium naturally has a positive void reactivity coefficient. High void reactivity coefficients cause overheating in the reactor core and lead to sodium boiling. Overheating is an issue in part because of the high expansion factor of sodium during its evaporation, approximately 2000 at atmospheric pressure. This means that a miniscule amount of sodium boiling results in a large volume of sodium vapor that threatens harm to the reactor. In addition, this phenomenon happens within seconds, so preventative measures must be quick and accurate in order to ensure the safety of the core [11].

INNOVATIONS IN ASTRID TO IMPROVE COOLANT SAFETY

Now that the two key issues associated with the use of sodium coolants have been identified, the duty of nuclear energy researchers is to minimize their repercussions. While there are many proposed solutions to sodium risks, temperature-resistant robots, acoustic detection, and ultrasonic detection have made the most progress in detection and prevention.

Temperature-Resistant Robots

Because sodium coolant is opaque, it is difficult for scientists to accurately inspect the reactor's core. To combat the potential of sodium leaks and to overcome the obstacle posed by sodium's appearance, special robots have been designed to work within the coolant. The robots are used to do in-service inspection, monitoring, minor repair, and data collection. The data collection allows the scientists to analyze the state of the reactor, and the design of the robots allows them to reside within the coolant. The robots have outer layer parts made of materials, such as specialized stainless steel and silicon-based alloys, that are able to withstand interaction with sodium and radiation. Stainless steel is a good choice of material for the robots because sodium is not corrosive to stainless steel and will not cause damage. Also, the material selection must be such that the robots are able to withstand long periods of intense heat and radiation without compromising the technology. Stainless steel also meets both of these requirements, furthering the feasible applications of the material and ensuring that these robots will be available when SFRs are built. More sensitive parts of the robots, such as wiring, are enclosed and protected from damage [12].

Temperature-resistant robots are used to inspect the nuclear reactor and find potential leaks, preventing meltdown situations in the core. Because these robots remain in the sodium coolant during the running of the reactor, inspection and repair can be conducted without the difficulty of entirely shutting down the reaction or exposing the sodium to air or water. In the situation of deep inspection, recommended twenty days out of every year, the reactor will go into cold shut down configuration, where the temperature is decreased to about 200 degrees Celsius, slowing the reaction enough to allow for better control and repair [12]. These inspections can detect issues such as sodium leaks or basic weaknesses in reactor structure. These preventive measures allow the nuclear reactor to be increasingly safe and lengthen the life of the reactor. The responsibility of a nuclear facility is to ensure the safety of the public that they serve and the environment that they inhabit. Temperature-resistant robots provide safety measures that work to meet these sustainability goals.

Acoustic Detection

One of the main characteristics of sodium boiling is the presence of bubbles in sodium coolant. These bubbles of sodium vapor form on the walls of the reactors and later detach from the wall, deforming slightly and creating an oscillation. All three of these phenomena, the formation, detachment, and oscillation, each create a unique sound that can be detected within the boiling loops.

The technology that has been tested in French reactors, such as Rapsodie, to detect sodium boiling is known as acoustic detection. Acoustic detection uses variations in sounds waves to detect changes in composition and location of the sodium coolant used in SFRs. This can be used to detect both sodium leaks and sodium boiling, and indicate that a response is immediately needed to prevent a sodium blockage from occurring [11]. Safety is the priority when using nuclear energy, and this technology employs preventive measures to lower the threat of nuclear crisis.

General boiling occurs when sodium boiling is seen throughout the entire cross section of the reactor assembly. This type of boiling results in lower frequency waves that can be easily detected by acoustic detection, as simulated in experiments on French reactors. Hot spot boiling, on the other hand, is more difficult to detect because it so rapidly develops into localized boiling. Localized boiling occurs when saturated boiling conditions are met in certain sub-channels of a reactor assembly cross section. Because research is being done on both of these boiling phenomena, scientists predict that acoustic detection will be able to accurately detect both types of boiling. Research now is largely focused on increasing the reliability of acoustic detection, especially in the realm of hot spot boiling [11].

Ultrasonic Detection

Another technology used to ensure safety of the nuclear reactor is ultrasonic detection. This detection differs from acoustic detection in that it sends waves through the sodium rather than detecting waves from the sodium. The technology is operated either externally or internally from the reactor to detect variation in the composition and location of sodium coolant.

External detection is more desirable than internal detection because external detection takes place within a gas environment. The sensors do not then have to be designed to withstand the radioactive and high temperature environment of the core that would inadvertently increase the cost of production and increase difficulty of design. External detection sends ultrasonic waves through the coolant and detects changes in propagation in order to check for the position of structures immersed in the sodium coolant, to check for cracks in the walls of the core, and to check for proper welds. This would greatly increase the effectiveness of in-service inspection and repair [13].

Although external ultrasonic detection is ideal, internal detection is required to ensure that all welds can be inspected during operation of the reactor. One of the most important structures to inspect in a nuclear reactor is the strong back. The strong back is a structure that resides in the sodium coolant and supports the core. In order to inspect this structure, ultrasonic sensors can be placed in the box and rim structure of the strong back so that the sensor can have direct access to all the welds on the structure [3]. The sensors can also be used to detect migrating bodies in the sodium, to detect cracks in the reactor's structure, and to properly position robots that are placed in the sodium. These sensors must also be resistant to the high temperature environment and radiation that is present in the reactor core [13]. While this is a difficult task to overcome, progress in this research area has scientists predicting that sensors will be available for use in future SFRs.

Ultrasonic technologies ensure that no sodium leaks will go undetected, thus preventing unwanted sodium reactions in the core. The reactor structure's strength and position will also be continuously checked, allowing robots to quickly and accurately strengthen and repair the core before further damage is done. These preventive measures lengthen the time the reactors are able to be run and make the reactor investment more economic. This follows the Generation IV Guidelines in the area of sustainability, ensuring not only the physical safety but also the economic feasibility of nuclear reactors.

SOCIETAL BENEFITS OF SODIUM COOLANTS AND SFRS

Technologies like temperature-resistant robots, acoustic detection, and ultrasonic detection can be used to increase the safety of sodium coolant and avoid disasters, such as sodium boiling and sodium reactions. Using sodium as a coolant in fast reactors yields the greatest amount of energy with the least amount of fuel, thereby optimizing efficiency and creating economic and environmental sustainability. Compared to the gas, lead, or water reactors, sodium is thus the most feasible.

The high reactor safety of SFRs is supplemented by economic benefits that result from having a lower-cost reactor. For example, the low cost of sodium coolant will lessen the startup cost of the reactor, and the safer preventative measures will increase the return on investment. This, along with the high-energy yield, will make nuclear energy more competitive as an affordable, sustainable energy source.

With the improvement of sodium coolant and SFRs, the Generation IV goals of reaching sustainable nuclear energy will soon be met because the risks will be low enough to justify using technologies like sodium coolants. Once the research associated with sodium coolants is complete, the risks of using sodium will virtually be eliminated. As a result, SFRs will be ready for commercial energy production and provide society with an energy source free of greenhouse gas emissions.

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