Systematic Review: Thorium Molten Salt Reactor 2016-2020

Achmad Farid Wadjdi, Sigit Permana, Eko Misrianto

Abstract: This study seeks to understand the Thorium Molten Salt Reactor (TMSR) readiness as a Thorium Power Plant. We explore the papers published in 2016-2020 to answer questions about the author's concern areas and issues related to the development of the TMSR. We reviewed the corpus of 242 papers out of 977 papers identified from reputable publishers. We present the research themes and trends of TMSR as a proposed power plant system, allowing future work to move forward as research support continues to evolve. The findings indicate an increasing trend of TMSR research mostly in reactor materials, tools, database enrichment, reactor type and design, neutronic, fuels, thermal-hydraulics, and safety/safeguard features. The polarization of research sentiment is 53% positive and 28% negative. We get an annual TMSR-1000MW(e) production cost figure of 3.01 cents/kWh, the total annual cost of $230.15 million, and the total plant cost of $3,507.84 million. We conclude that the TMSR as a power plant system meets technical feasibility, low power cost, and good fuel utilization. The recommendations are the need for collaborative research in advanced materials for the TMSR environment and necessary codes/standards in developing, licensing, waste management, security assurance, and safeguards of TMSR.

Index Terms: nuclear power generation, research and development, systematic reviews, thorium molten salt reactor

1. INTRODUCTION

THORIUM based power generation has attracted the attention of energy authorities in Indonesia. In the context of energy security, the Ministry of Defense views the importance of managing current and future national energy supplies [1]. One of the future energy sources is thorium. Various discourses echo that thorium-based power plants use a type of IV generation reactor with advantages in modularity, safety, relatively cheap, and cleanness (to reduce carbon gas emissions) [2]. For Indonesia and several countries that have not implemented nuclear power plants, the abundant source of thorium is a chance to ensure their national development sustainability [3]. Therefore, the discourse of a thorium power plant is always directed more towards economic and safety prospects. However, even if there are vendors to declare readiness [4], the national energy policy authorities still have to face the stigma of 'public acceptability' - related to the risk of accidents [5] and the dangers of nuclear waste [6] to be incorporated into regulation. - (email: eko.misrianto@kemhan.go.id) One of the reactor designs in the research spotlight is the Thorium Molten Salt Reactor (TMSR), associated with the 233U/thorium fuel cycle using all neutron energy spectra (the concept of thermal, epithermal, fast, and mixed). There are two TMSR classifications offered, reactor designed using thorium fueled liquid [7] and solid-fueled thorium [8]. Many experts have reported simulation research and experiments, fuel cycles, irradiation tests, and fuel fabrication attempts in various publications that attest to the significant experience of TMSR [9]. Also, they predict that new research on TMSR for electricity will continue to increase to realize a sufficient level of commercialization and tight security [10]. Therefore, understanding TMSR development research trends in the last five years is valuable knowledge that can guide researchers, practitioners/investors, and energy policy authorities. This study aims to improve understanding of TMSR readiness by reviewing the publication of the 2016-2020 period, related to the theme, relevance, and sentiment of TMSR as a Thorium Power Plant. There are three research questions:(1) What areas are the researchers concerned about TMSR development? (2) What are the issues and sentiments in TMSR development research? (3) What are the recommendations offered? We hope that the results will provide an overview of TMSR research trends' current state and provide valuable insights to academics, practitioners, and energy authorities on various TMSR research topics as a power generation option.

- *Achmad Farid Wadjdi is with the Defense R&D Agency-Ministry of Defense, Jakarta Selatan, 12450, Indonesia, PH +62-21-7502083. E-mail: farid.wajedi@kemhan.go.id).*
- *Sigit Permana is with the Defense SciTech Center, Defense R&D Agency, Ministry of Defense, Jakarta Selatan, 12450, Indonesia. Email: sigit.permana@kemhan.go.id*
- *Eko Misrianto is with the Defense SciTech Center, Defense R&D Agency, Ministry of Defense, Jakarta Selatan, 12450, Indonesia*

2. METHODS

We refer to Mignacca and Locatelli [11] with slight modifications in compiling and selecting the literature. We adopt a two-step analysis in conducting analysis; first, we analyze quantitatively about trends, themes, and sentiments based on all selected documents (corpus) using text analysis of MaxQDA [12]; second, we discuss only the documents according to each theme and synthesize the result qualitatively by providing descriptive narrations.

2.1 Literature identification and selection

We identify literature published in academic journals through online searches on Scopus, Science Direct, SpringerLink, TandFonline, Proquest, IOPScience, and EBSCO. The term sought includes "thorium molten salt reactor OR TMSR." Table I provides the search string usage and the number of papers found in the different databases. We also refer to the official web such as IAEA, ORNL, NRC, and OSTI. Google and Google Scholar are used to search for additional scientific publications based on a quick review of the search results' details. We used a custom search string according to the query script rules for each database. The search is limited to "peer-reviewed journal articles" published in "2016-2020". We filtered the document using exclusion criteria (Non-TMSR related matter nor themes, uncomplete article, and published before 2016). From the 977 identified documents, we obtained 321 unique and relevant documents.

TABLE 1.
IDENTIFIED DOCUMENTS

DB	Search String	Result
Scopus	TITLE-ABS-KEY (thorium AND "molten salt reactor")	249
Science Direct	thorium molten salt reactor	361
Springer Link	thorium molten salt reactor within Article	171
Tand Online	[All: thorium molten salt reactor] AND [Publication Date: (01/01/2016 TO 12/31/2020)]	63
Proquest	ab(thorium OR Th) AND (molten salt reactor)	74
IOP Science	thorium molten salt reactor	15
Ebsco	thorium molten salt reactor	28
Official web*	thorium molten salt reactor	16
	Identified documents	977

*We found articles in the Official Web of Nuclear Organizations, such as IAEA, ORNL, NRC, and OSTI.

2.2 Text mining, Coding and Sentiment Analysis

We obtained a corpus of 242 papers through a quick review of 321 documents - retracting 79 documents due to unclear methods or conclusions. We use the lexical search function to scrutinize the corpus before coding. This search is similar to "search string" in collecting initial documents, but lexical search focuses more on the corpus with a specific variable value. We map the lexical search result in terms of the word cloud and word frequency, and then we interpret to structurize themes of codes. The code will become the basis of our analysis to answer research questions and conclusions. In terms of paper tendency, three reviewers were free to code the "polarity of sentiment" of the sentences or paragraphs in each paper's abstract and conclusions. Sentiment polarity refers to the definition of "a reviewer's decision to judge whether a sentence or paragraph is negative, positive, or neutral [13] in tone to TMSR development."

3. RESULTS AND DISCUSSION

3.1 The code structure of the research concern

In the initial analysis, we need to obtain the corpus's dominant keywords using the "word-cloud" technique [14]. The results will be a guide in the structuring of coding. The corpus of this study refers to 242 papers. We interpret word-cloud and word-frequency into code structures through discussion and refer to reactor technology's knowledge base. Fig. 1(a) shows the corpus and its trend, and (b) the word-cloud of the corpus, which we then interpret into the code structure in Fig. 1(c). The code structure is crucial in systematizing the achievement of objectives and provide answers to this research question. Each code contains segmented documents from the corpus that form a specific theme. We then focused on themes and sub-themes related to the proposed TMSR system for power generation in reactor parameters. In the discussion section, we will review and discuss more on this category.

3.2 Publications trends, themes, and tone

We show the results of text-mining that provide publication trends in the corpus by region, country, and sentiment - sequentially in Fig. 2 (a), (b), and (c). It shows the trend resulting from text-mining, which lexically refers to each document in the corpus. For example, in Fig. 2(a), this trend does not indicate the amount of TMSR research in a region but rather indicates lexical inference that there is TMSR research activity in a region. With such a context, we see that during 2016-2020, TMSR research activities in the world tended to increase. Research activity in Asia-Australia (202 papers) is slightly more than in America (199 papers) and significantly outperforms Europe (146 papers), whereas until 2017, according to [209], the American region is the most dominant. However, in Fig. 2(b), trends based on country activity show that the US remains the most active and dominant in conducting TMSR research among all countries. Fig. 2(b) shows the top eight countries related to the Molten Salt Reactor research activities. Fig. 2(c) refers to the definition of polarity sentiment, where three reviewers' decisions assessed the corpus (N=242), which 53% favorable and 28% negative. However, whether the papers' conclusion is negative, we see that the authors' focus is consistent with the development of TMSR.

3.3 Reactor Design

Thorium-based fuel reactor designs are attractive because of the abundance of thorium sources in nature [15], projected low-cost electricity [16]–[18], and successful experiments with liquid salt reactors (MSRE) [19], and their recent developments in processing have answered most feasibility questions. There are several dues that a feasibility study on the TMSR technology component has been carried out[20]–[22]. There are also many reactor designs being under research development. Magwood [18] mentioned technical characteristics of TMSR design: thermal/fast neutron spectrum, fluoride or chloride salt coolant, 700-800C of outlet temperature, closed fuel cycle, and 1000MW. According to Vijayan [23], BARC is designing IMSBR (Indian Molten Salt Breeder Reactor) 850MWe, which some of the powerful technology under research are neutron transport, characterization studies, thermal-hydraulic, preparation and purification of salts, instrument development, and Online chemistry control techniques.

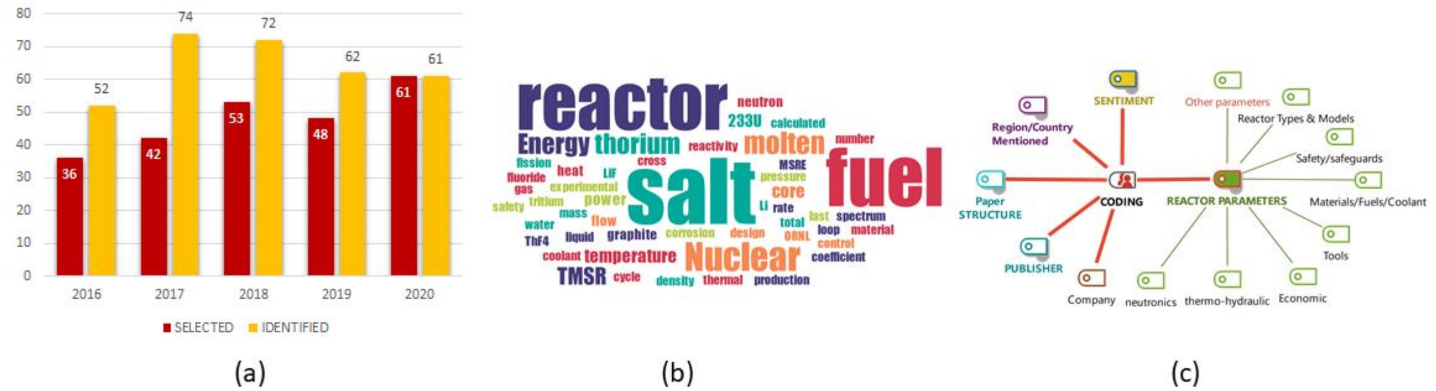

FIG. 1. PROCESS OF STRUCTURING THE CODES: (A) THE CORPUS BY YEAR, (B) WORD-CLOUD OF THE CORPUS, AND (C) THE CODE STRUCTURE OF THIS STUDY

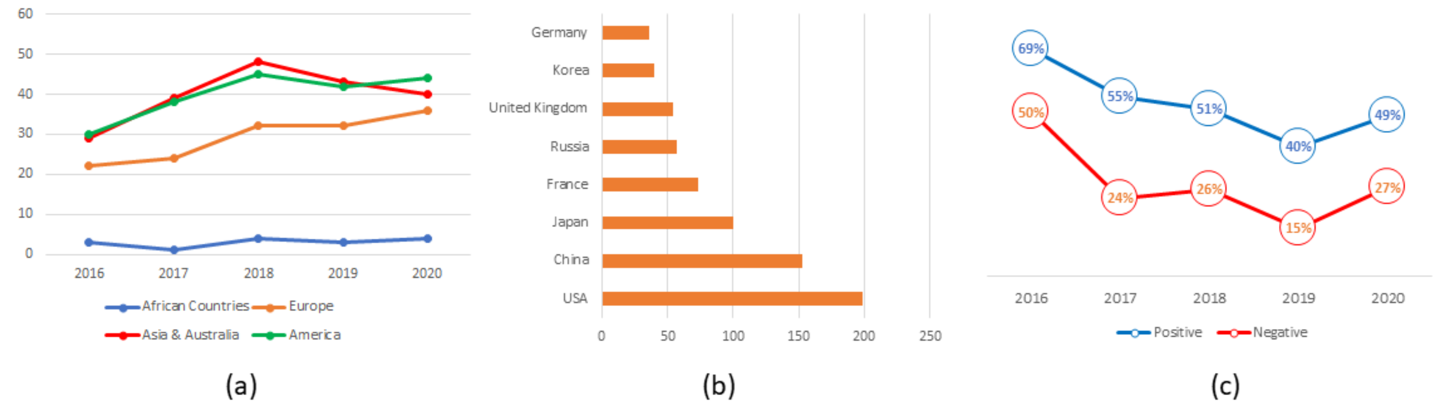

FIG. 2. (A) PUBLICATION TRENDS IN THE CORPUS BY REGION, (B) COUNTRY MENTIONED IN THE CORPUS, AND (C) THE SENTIMENT TREND

Quantification of nuclear data-induced uncertainty of neutronic parameters and its reduction using measurement data obtained at critical facilities have been critical technical subjects in fast reactors development [24]–[26]. Meanwhile, the development of TMSR features is also getting research focus and attention, such as the freeze valve system [27]–[29] and tritium control [30]–[36] for an advanced safety feature, thermal-hydraulic/neutronic phenomena [24], [26], thermo-dynamic/physical properties [37], [38], and conceptual design development [18], [29], [39]–[47]. In MSR commercialization, Forsberg and Peterson [17] have provided target directions for developing new reactors to obtain government support. The goals are (1) to increase generation revenue by 50% to 100% relative to a baseload nuclear plant with a capital cost similar to a light water reactor, (2) to enable a renewable power grid with zero carbon, (3) no potential for fuel failure so that there is no potential for the release of radionuclides outside the crash site, and (4) offer a pathway to a more advanced energy system. With such criteria, TMSR designers need to consider variations in reactor power capacity. The choice of a molten salt cooler should allow for short-term reactor designs so that large-scale fuel failures cannot occur, and thus large-scale off-site releases of radionuclides cannot occur. In extreme accident conditions, the heat of decay can be carried passively into the environment at temperatures well below the fuel failure temperature and thereby avoiding the potential for massive scale release of radionuclides. Meanwhile, several experts added the importance of increasing thermal efficiency and modularization of reactor design [48]. Albeit theoritically thermal efficiency of MSR is up to 80%, reactor design with a thermal efficiency of about 45% will be suitable for commercializing a power plant [17], [46], [48]–[53]. The higher the reactor design's modularity will attract immense market interest[11], [18], [21], [54]; for example, Zheng et al. [21] estimate replacing the reactor core for seven years is feasible. Hussein [55] added that the commercialization of "deliberate small reactors" needs to refer to the revitalization of the nuclear power industry, which provides improvements in terms of "safety, construction, operation, and economy." Fig. 3 shows the MSR design trend, including liquid-fueled (TMSR-LF) and solid-fueled (TMSR-SF), which indicates increasing expert attention to MSR's advantage, especially the trend of liquid-fuel TMSR. We found only twelve MSRs' company designs mentioned in 55 of the corpus, with six companies getting more attention in scientific publications, as shown in Fig. 4 and Table 2. The most highlight is Thorcon Power. Thorcon is preparing to build a demonstration reactor for Indonesia's first power plant receiving the most publicity spotlight. Modularity, mobility, and MSRE as the basis of the design are the advantages of ThorCon. Based on the straightforward scale-up of the successful MSRE, Thorcon Power claims to be ready to build a demonstration of a full-scale 500 MWe ThorCon in Indonesia by 2025. ThorCon designed the MSR system in the hull of a shipyard, which some Indonesian authors [56]–[60] considered to be suitable for Indonesia or other island countries. Assuming efficient, evidence-based regulation, ThorCon can produce clean, reliable, CO2-free electricity at US$0.03/kWh — cheaper than coal [16], [50], [61].

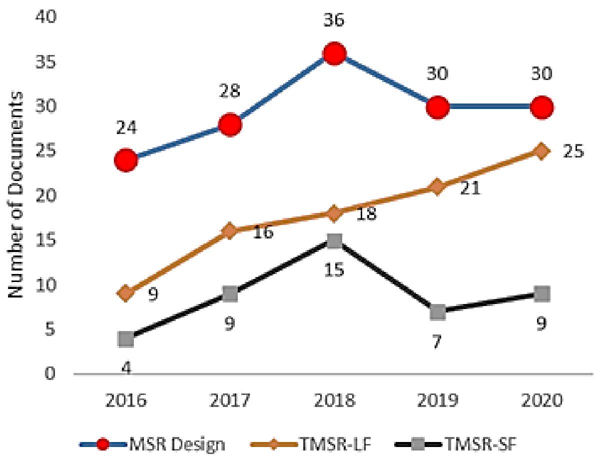

FIG. 3. THE TREND OF MSR DESIGN

As such, the complete thorcon design will provide an increase in productivity, quality control, and build time, whereby one extensive reactor system can generate approximately twenty gigawatts of electricity per year. Albeit there are arguments of handling the various possible casualty scenarios [62], including the most troublesome fission products [50], [61], [63], the challenges to the "safe" claims of Thorcon's design (and other company designs), including waste management systems[23], [49], [55], [64]–[67], must be real or at least evidence-based demonstration reactor data and not results simulation.

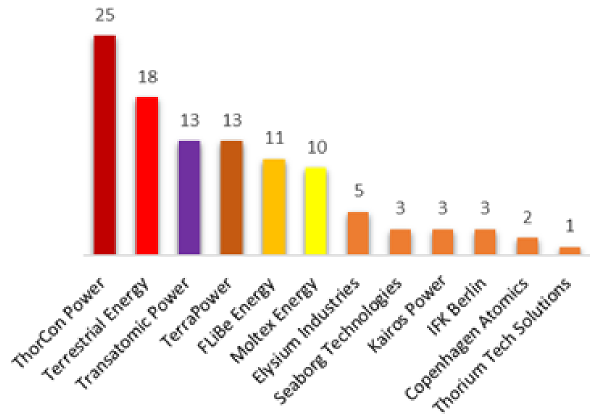

***Fig. 4**. The company mentioned in the corpus*

The design of the Terrestrial Energy and Transatomic Power reactor systems also received much attention [24], [68], [69]. Terrestrial energy develops Integral Molten Salt Reactor (IMSR) as a graphite-moderated MSR burner. The system is a modular reactor design with three versions of the power rating: 32.5 MWe for remote communities, 141 MWe for industry, and 291 MWe for ordinary electricity production[193]. IMSR with a thermal efficiency of about 50% uses liquid fuel with U-235 (<5% enrichment) dissolved in the fluoride salt. As with ThorCon, IMSR's inherent safety level is excellent because it does not rely on operator intervention. Table 2 shows some characteristic of the MSR system [24].

TABLE 2.
SOME CHARACTERISTICS OF THE MSR SYSTEMS

Company Name	Reactor Name	Description of Design	Docs
ThorCon Power, USA	ThorCon	Graphite-moderated Th+LEU burner, deployed by ship	25
Terrestrial Energy, Canada	Integral Molten Salt Reactor (IMSR)	Graphite-moderated integral LEU burner	18
Transatomic Power, USA	Waste-Annihilating Molten Salt Reactor (WAMSR)	ZrH-moderated SNF/LEU burner	13
FLiBe Energy, USA	Liquid Fluoride Thorium Reactor (LFTR)	Graphite-moderated two-fluid Th breeder	11
Moltex Energy, UK	Stable Salt Reactor (SSR)	Chloride-fueled Pu breeder, internal fluoride salt cooling	10
Terra Power, USA	Molten Chloride Fast Reactor (MCFR)	Chloride-based fast U-Pu cycle reactor	13
Elysium Industries, USA	Molten Chloride Salt Fast Reactor (MCSFR)	Fast spectrum, chloride salt-based liquid fuel	5
Seaborg Technologies, Denmark	Seaborg Technologies Wasteburner (SWaB)	Graphite-moderated Pu+MA+Th burner	3
Kairos Power, USA	KP-FHR	Pebble-bed type core with TRISO-fuel cooled fluoride salt	3
IFK Berlin, Germany	Dual Fluide Reactor (DFR)	Chloride or metallic-fueled Pu breeder internal lead cooling	3
Copenhagen Atomics, Denmark	Copenhagen Atomic Waste Burner	Graphite-moderated Pu+MA+Th burner	2
Thorium Tech Solutions, Japan	FUJI, miniFUJI	Graphite-moderated single-fluid Thorium breeder	1

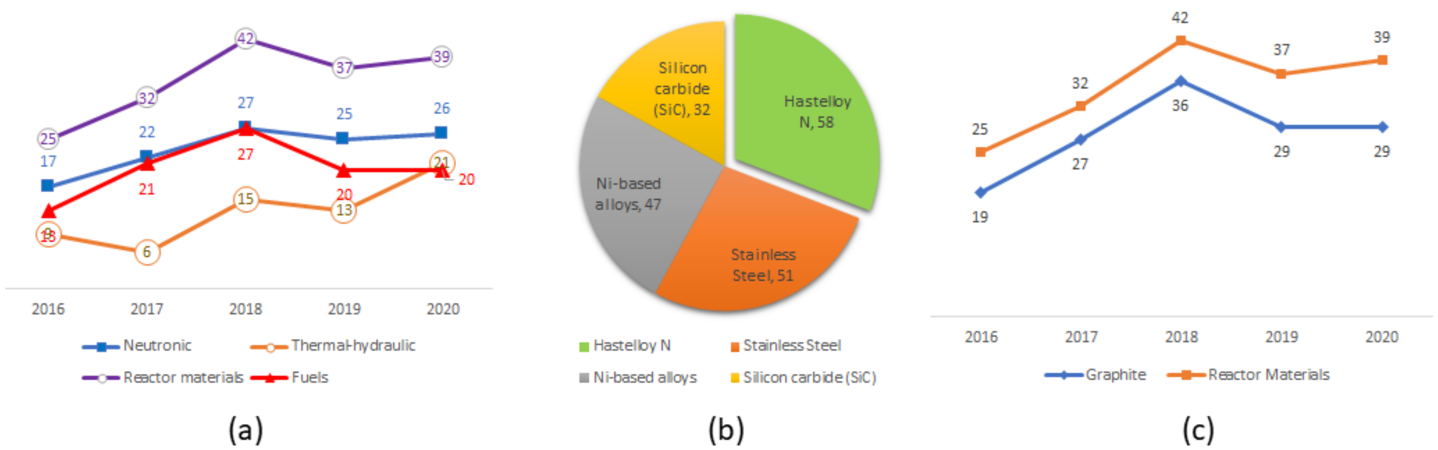

FIG. 5. THE TREND RELATED TO REACTOR PARAMETERS

Meanwhile, Moltexenergy [22], [30], [31], [44], [69]–[71] designed the Stable Salt Reactor (SSR) using molten salt fuel as a substitute for the solid pellets in conventional fuel assemblies, which provides the main advantage of safe liquid salt without the technical hurdles of managing mobile liquid fuels. Flibe Energy's design is a liquid thorium fluoride (LFTR) with a two-zone reactor, moderated by graphite, and a liquid fluoride salt solution containing fissile and fertile material [15], [24], [38], [44], [54], [65], [68], [69], [72]. Other companies, such as Elysium Industries[24], [70], [73], designs the 2500 MWth Molten Chloride Salt Fast Reactor (MCSFR), which operates in the fast spectrum. The main functions of the MCSFR are to convert weapons-grade Pu into fissile fuel, burn wastewater reactor fuel, and transmute durable fission products. The FUJI-233Um MSR uses a Th-233U fuel cycle, consisting of a core with hexagonal graphite blocks and standard fuel salts for the primary loop (7LiF - BeF2 - ThF4 - UF4). The overall thermal efficiency of the FUJI-233Um is around 44% [27], [74], [75]. Thorium Tech Solutions Inc. is preparing to commercialize the Fuji concept utilizing the Halden test reactor in Norway [76]–[82].

3.4 Reactor parameters

Fig. 5(a) shows that all parameters' trend is increasing, except the fuels, which are somewhat stagnant. The best trend is the reactor material. The theme of material demonstrates an increasing need to guarantee materials suitable for a molten salt environment. Besides that, the current advances in material technology to meet various complementary needs have also spurred a more varied choice of materials [11], [31], [42], [64], [67], [77], [83]–[94]. The materials most mentioned in the corpus are Hastelloy N, stainless steel alloys, and Ni-based alloys, see Fig. 5(b). The consideration of material selection mainly refers to its characteristics in the influence of the radiation environment, high temperature, and molten salt [95], for example, its resistance to corrosion swelling[96] and creep [97]. Currently, some of the materials, such as Alloy-800H, is considerate for use in nuclear systems with operating temperature up to 760 ◦C owing to its high-temperature strength and good resistance to swelling, corrosion, and creep-rupture [91], [97]–[101]. Graphite is a popular reactor material for core structural materials and moderators. The research trend of graphite during 2016-2020 is increasing; see Fig. 5(c. We have obtained 140 document segments from the corpus, which shows that graphite is a vital reactor material.

Since TMSR is generally still a conceptual design, and some of the available data only comes from test results in laboratory facilities or experimental reactors, researchers generally carry out tests and simulations with software or codes based on data coded in the nuclear database. In this case, we can understand how important it is to develop applications and enrich the TMSR-specific nuclear material database. Meanwhile, the thermal-hydraulic phenomena are also related to the neutronic and material composition, where these all phenomena are crucial in reactor design [24], [26], [75], [101]–[109].

3.5 The Advantages and Issues

We summarize the TMSR challenges outlined in the corpus in Table 3. Then, what is listed still needs evidence as a stimulus for research sustainability and also to convince the energy industry market.

TABLE 3.
THE ADVANTAGES AND ISSUES OF TMSR

Advantages	Disadvantages/questions
– High thermal-electric conversion efficiency – Inherent safety – Online reprocessing and refueling – Abundant resource of thorium – Modularity – 7Li to tackle Tritium issues – The high solubility of actinides in salt – Superior breeding capacity – Low waste production	– Different technical routes of fuel management, such as the selection of carrier salts, the enrichment of uranium, with or without thorium, and the recycling necessary of spent nuclear fuel – Lack of standard or codes – Technical challenges and high costs to produce 7Li enrichment – Question about the waste management – Question about licensing standard – Question about the financing high capital cost

3.6 Economic of TMSR

Scientific literature about the economics of MSRs is very scarce and almost non-existent in terms of their financing [11]. For that reason, in this section, we will describe a simple approach of the economic calculation of TMSR electricity generation per kWh by referring to the MSRE (experimental reactor) operated by ORNL with several assumptions of changes in costs between 1966 and 2019. We estimate the cost of MSR for electricity generation is as follows:

1. MSRE was built in 1962 and has given its report on the

total cost plant around USD110.695 – 114.412 million [110]. Then the MSR cost prediction for the 1000 MWe generation assumption in 2019 is estimated at $3,507,842,344.18

- Total plant cost = plant reactor cost + cost of the processing plant
- Total plant cost (1966) = $ 114,412,000 + $ 5,300,080
- Total plant cost (1966) = $ 119,712,080

The ratio of the Producer Price Index for energy between 2019 (107.5) and 1966 (31.5) is 3.4126984127.

- Total plant cost (2019) = ($ 119,712,080) x (100 / 3,4126984127) = $3,507,842,344.18

2. The ORNL report [110] also estimated annual operating and management costs of $721,230; then O&M in 2019 after calculating the 6% amortization becomes $230,146,759 (excluding Fuel).
   - Variable Annual Cost = $209,013,043
   - O&M cost (2019) = ($721,230) x (100 / 3.4126984127) = $21,133,716
   - Total Annual Cost (2019) = $230,146,759 (excluding Fuel)

   If energy produced = 1,000,000(8760hr) = 8.76x10^9 kWh, then cost per kWh = 3.10 cents.
   - Cost per kWh = $230,146,759/8.76$x$109= $0.0263 = 2.63cents (excluding Fuel)

   According to [88], the price of thorium salt fuel with Uranium Enrichment 5% is 0.47cents/kWh
   - Cost per kWh = 2.63 + 0.47 = 3.10 cents

Our calculation result is similar to Samalova, Chvala, & Maldonado [111], who points out that the annual cost of MSR is $230.15 million, which is almost half times lower than the existing present electricity generation. Also, the overnight cost of MSR per kWe comparable with AP1000. The smaller MSRs have a significantly higher overnight cost per kWe, but their lower total overnight costs are their main advantage for specific applications. They also emphasized that nuclear power plants such as PWR (Pressurized Water Reactor) are more sensitive to fuel prices than MSR. Raditya and Hiendro [4] reported their calculation of the TMSR500 with 2 x 500 MW capacity. The results show that TMSR is feasible to build in West Kalimantan. The total cost of production of the TMSR500 is $0.0276/kWh (2.76 cents/kWh), and the NPV value is positive in each scenario in which the payback period is only 5.8 to 6.5 years less than the project life.

4. CONCLUSIONS

This study reviewed 240 papers published by prestigious international publishers 2016-2020 to understand TMSR research areas that concern researchers. We have structured the areas of interest, where most of them are on: reactor materials, tools, database enrichment, reactor type, neutronic, reactor design, fuels, thermal-hydraulics, and safety/safeguard features. Other themes, such as the economics of the TMSR, received few reviews (less than ten papers). We realize that research from the Asia and Australia region has outperformed America and Europe, but research from the USA is still dominant compared to other countries. This study also shows the polarization of research sentiment in the last five years, where 53% are positive, 28% negative, and the rest are neutral. The significant issues and challenges that stand out are the need for collaborative research in advanced materials for the TMSR environment and necessary codes/standards in developing, licensing, waste management, and security assurance of TMSR, including safeguards. For an economic overview, we describe a simple calculation model given the limited data availability, which the result shows an annual cost of 3,1 cent/kWh based on TMSR 1000MWe generation. Most of the reactors, such as PWR, were initially built because there was a military stimulus to the need for a defense doctrine that only applies to nuclear weapons countries. Later, its commercialization encourages non-nuclear weapons countries such as Japan and Korea in Asia, Germany, Europe, and worldwide. Then, we realize that the stimulus for TMSR is emerging due to fears of climate degradation from the overuse of fossil fuels. The use of MSR will soon become widespread if its economic and security features can immediately convince decision-making authorities.

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Achmad Farid Wadjdi was born in Indonesia on March 20, 1963. He received the nuclear engineer degree from Gadjahmada University, Yogyakarta, Indonesia, in 1987; a Master's degree in research operation from the UPN "Veteran" Jakarta Indonesia, in 2000; and a Ph.D. degree in Research Management from the Binus University, Jakarta, Indonesia, in 2015. Currently, he is a senior researcher at the Defense R&D Agency - Ministry of Defense and a lecturer at the Military Engineering Faculty of the Indonesian Defense University, Bogor, Indonesia. He was the Head of the Defense Center for Data and Information, and the Defense Codification Center Head at the Ministry of Defense, Indonesia. His research activities in the last five years are strategic materials, advanced materials for small gun barrels, passive radar, social and political engineering of the state defense policies, big data analytic applications for national defense, development of cybersecurity framework in the military, integrated artificial intelligence and neuroscience for the Indonesian military, design of advanced propulsion system, and development of applied decision-making system for the Indonesian military. He is a certified member of the Indonesian Research Reviewer Association.

Sigit Permana was born in Jakarta, Indonesia, on Augustus 16, 1974. He received the industrial engineer degree from College of Industrial Management, Ministry of Industry, the Republic of Indonesia in 2005; Master's degree in industrial engineering from the Mercu Buana University, Jakarta Indonesia, in 2017. He is currently a researcher at the Defense SciTech Center - Defense R&D Agency - Ministry of Defense. His research interests are applied ergonomic in the military, industrial nuclear engineering.

Eko Misrianto was born in Indonesia on January 5, 1967. He received a chemistry degree from Pattimura University, Indonesia, in 1994; Master's degree in defense logistics management from UPN "Veteran" Jakarta Indonesia, 2010. Currently, he is a State Defense Analyst at the ministry of defense, Indonesia. He was the head of the sub-division of combat power, head of the sub-division of supplies and communications at the Ministry of Defense's research and development agency, Indonesia. His research interests include weapons systems & support, combat vehicles, reconnaissance technology, and applied military technology for national defense. His research project involvement in the last five years includes UAV technology for surveillance, intelligence, Medium Altitude Long Endurance (MALE), glide smart bomb, small jet engine and rudder fin, rocket control, main battle tank, retrofitting and vehicle repowering, armored BTR-50, Manpad weaponry, and Combat Swimmer Vehicle (CSV).