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Global Consumption of Flame Retardants and Related Environmental Concerns: A Study on Possible Mechanical Recycling of Flame Retardant Textiles

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Abstract: Flame retardants (FRs) have been around us for decades to increase the chances of survival against fire or flame by limiting its propagation. The FR textiles, irrespective of their atmospheric presence are used in baby clothing, pushchairs, car seats, *etc.* The overall FR market in Asia, Europe, and the United States in 2007 was around 1.8 million metric tonnes. It is estimated that the worldwide consumption of FRs will reach 2.8 million tonnes in 2018. Unfortunately, a sustainable approach for textile waste, especially in the case of FR textiles, is absent. Incineration and landfill of FR textiles are hindered by various toxic outcomes. To address the need for sustainable methods of discarding FR textiles, the mechanical recycling of cotton curtains was evaluated.

Keywords: flame retardant (FR); textiles; mechanical recycling; cotton; carbon emissions

1. Introduction

For decades, flame retardants (FRs) have been used to increase the chances of survival against fire or flame by limiting its propagation. FRs in textiles are used irrespective of product type for reducing their flammability, for instance, in baby clothing, pushchairs, car seats, *etc.* [1]. FRs may exhibit a different chemical composition: They may contain halogens (bromine and chlorine), phosphorus, nitrogen, aluminum, magnesium, boron, antimony, molybdenum, or recently developed nano-fillers. The total consumption of FRs in 2006 in Europe was estimated at 465,000 tonnes [2], and the overall market for FRs in Asia, Europe, and the United States in 2007 was around 1.8 million metric tonnes [3]. It is estimated that the worldwide consumption of FRs will reach 2.8 million tonnes in 2018 [4].

The majority of FR textiles are classified as either non-/semi-durable or durable finished fabrics. Their durability is dependent on the binders used in pre-treatment finishes. Non-/semi-durable FRs find applications in the domestic sector, mostly in disposable medical gowns, curtains and carpets, upholstery, bedding, and party costumes. On the other hand, inherently durable FR textiles are also used in high-performance applications [5]. Like other industries such as the building product industry, the textile industry has responded stringently to the requirements of healthcare and fire safety. A great need and demand of fire safety and healthcare organizations has moved the current textile industry to infuse resources and chemicals into the textile products that may harm the environment rather than protect it [6]. The requirement of lifelong attributes of FR textiles has also resulted in an increased usage of chemicals. Indeed, many chemicals degrade by the exposure to some natural phenomena, such as light, microbial activity, and the reaction with air or water. However, commercially claimed FRs are found in daily surroundings. Scientific studies have shown that FR products are the source of different environmental presences and pollution, such as air [7], dust [8], surface water [9], drinking water [10], and wastewater pollution [11]. An adequate amount of FRs has also been found in some fish species [12,13] as well as in human breast milk [13]. Meanwhile, many studies on the chemicals used to bring special fire safety and healthcare attributes to textiles have shown links to health effects from asthma to cancer [6].

It is important to understand that, even with adequate evidence that toxicity can prohibit a FR compound or a toxic chemical, the emergence of new FR products is inevitable. For instance, organo-halogens, including the polychlorinated biphenyls (PCBs), chlorofluorocarbons (CFCs), and phosphate FRs like Tris (2,3-dibromopropyl), are banned worldwide [6,14]. A toxicity check involves a long procedure; in addition, banning any toxic chemical product involves various political and economic issues. However, one should remember that FRs do save precious lives. Even many FR products are now available, claiming to have environmentally friendly applications, but their application somehow involves toxic chemical procedures and leads to high CO_2 emissions. In this context, there is a need of stringent environmental regulations on FR production, consumption, and post-consumer phases.

Additionally, the persistence assessment of a FR involves the occurrence of chemicals that are released into water, air, and soil. Many people are exposed to FR textile products in homes and workplaces every day, including furniture, curtains, mattresses, and even apparel. Additionally, most of the FRs are extremely persistent; they transfer easily from furnishings, appliances; and buildings into dust that eventually we breathe. The information on the exposure of FRs from textile products to environmental pathways is scarce. Unfortunately, the existence of FRs is neglected on a daily basis in spite of risks induced with FRs during the exposure from household textiles by human contact through the skin, by inhalation, and especially via hand-to-mouth transfer of substances emitted to the atmosphere during the lifetime of FR textiles (see Figure 1). Moreover, the discarded FR textile products pose a potential concern of leaching through soil as the rainfall permeates underground to intoxicate the surface and groundwater [15]. On the other hand, the risks of toxic gas emissions during incineration are likewise neglected. Accordingly, the risks associated with the exposure of low concentrations, to such ecosystems as small lakes and streams with a low flow rate and to the organisms thereof, are greater in cold climates than in warm climates [16].

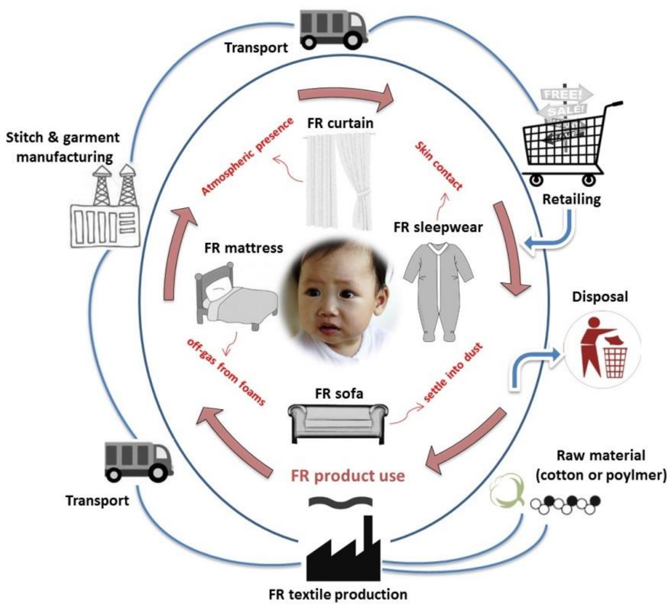

Figure 1. Life cycle of flame retardant (FR) textile products.

According to Defra [17], a better alternative to disposal is to recycle discarded products, which is a more interesting approach rather than producing new FR products. When it comes to waste management hierarchy, from Figure 2, direct disposal is at least a desired option for the waste and discarded products. In the case of textiles, they are being used as an alternative fuel energy source. Indeed, incineration is an energy recovery system of biodegradable materials, which avoids the negative effects of landfill (methane emissions), but has a limited positive effect in the end from saving limited amounts of energy or materials [18–20]. Incineration of FR textiles would also be favorable instead of the landfill; however, incineration of the FR textiles would decrease the energy yield and produce toxic emissions. Likewise, the FR from textile products entering the environment are usually not quantified, whether they are subjected to disposal in a landfill or to the incineration and volatilization process. Meanwhile, the recycling or reuse of FR textile products can be a supportive pathway to decreasing environmental pressure as well. Even though textile recycling is one of the oldest kinds of recycling, the average rate of textile recycling is still rather low. The rate of recycling is different from one country to another, depending on various factors such as recycling education and infrastructure [21].

Figure 2. The European unions waste hierarchy (adapted from: Defra [16]).

Incineration and Recycling of Textile Products

In the literature, little evidence of the environmental benefits can be found on textile recycling and reuse as second-hand textiles where no reprocessing is involved. Recycling of textiles into wipers or filling materials can be found to some extent [22]. Lack of advancement in textile recycling and accessibility of cheap fabrics in markets also restricts the possibility and interests in recycling techniques [23]. In addition, it is anticipated that technical textiles are not designed for recycling, as it is difficult to distinguish textiles in the mechanical recycling process (even in manual process) due to the addition of numerous materials. Conditionally, the sorting of such textiles for reuse purposes becomes even more difficult because of the lack of aesthetic and specialized skills [24]. Numerous life cycle assessment (LCA) studies can be found on the assessment of the environmental impacts of clothing [25,26]. Indeed, the LCA tool has evaluated the relative benefits during the disposal and or recycling process of some textile products. In LCA case studies, a complete lifecycle of polyester fabric (1 kg) was found responsible for beyond 30 kg of CO_2 equivalents released into the environment and cotton fabric to release about 20 kg of CO_2 equivalents [20]. However, there is a great lack of LCA studies conducted over the end-of-life of textiles and the environmental impacts of textile recycling, as there is a scarcity of conclusive “closed-loop” recycling assessment studies [27]. Nevertheless, textile waste recycling is found to be more environmentally favorable than incineration [28]. The recycling of textiles into fibers saves around 4 kg of CO_2 equivalent per kg textiles compared to direct disposal [29].

The global warming potential is 8.3 kg of CO_2 equivalents higher when disposed to landfill compared to the incineration of cotton fabric [30]. Reuse of textile products (direct or indirect) not only reduces the environmental pressure, but also considerably lowers the global warming potentials by 15 kg of CO_2 equivalents per kg of textile [31,32]. Indeed, changing landfill to incineration with the energy recovery of textile waste products reduces the total energy consumption of textile lifecycle by about 2% to 6%, while textile reuse decreases this energy consumption by 20–60%. The greenhouse gas emission is also reduced to a great extent when reusing textile waste, with a reduction of around 1682 to 13,000 kg of CO_2 equivalents per tonne of textile waste, and recycling reduces this value from 1200 to 1800 kg of CO_2 equivalents per tonne of textile waste [33–36].

This study deals with the possible recycling of FR-treated cotton curtains, instead of being disposed for incineration. The proposed mechanical recycling technique of FR textiles would replace the incineration process, which is the dominant method of FR textile waste treatment in most European countries. The proposed study is carried out only to assess the CO_2 emissions on a preliminary basis. In addition, the study investigates the proposed mechanical recycling process of FR products to assess the overall carbon footprint of the product in comparison to the incineration process at disposal.

2. Materials and Methods

One of the primary needs of human beings is clothing, which generates carbon footprints in each phase of the textile product's lifetime. Among those phases, production, usage, transportation, consumption, and disposal of textile products increases a considerable environmental pressure [37]. In spite of this, recycling textile products in most European countries is carried out by a mechanical recycling system (from shredding to yarn manufacturing). In many European countries, such as the Nordic countries, the mechanical recycling systems are more or less non-existent due to high operating costs and a lack of available recycling technology [38]. The mechanical recycling of FR textiles may raise hazardous issues while sorting and processing each textile product, as there is a lack of investigations. For example, FR textile products go through different processing steps dependent on FR and fiber types, which may be obstacles to mechanical recycling. The aforementioned study by Palm *et al.*, 2015 [38] made a distinction between textile-to-textile recycling and other textile recycling. Whereas, in textile-to-textile recycling, the recycled textile fibers are used to produce new textile products, such as apparel and home textiles, in other textile recycling, the recycled textile fibers are used to produce lower-grade textile products, such as thermal insulation and acoustic textiles.

Traditionally, there were among 300–400 FR chemical systems produced for different applications [39]. In the textile domain, the FR cotton fabrics are usually produced by a chemical surface treatment as a textile finishing process, which gives durability to various washings or laundering processes. The durability of FR finishes for cotton fabrics can be defined as able to withstand 50 washings, while organophosporus FR compounds are found to withstand more than 50 washes. The organophosphorus FR compounds such as cellulose reactive methylolated phosphonamides and tetrakis (hydroxy methylol) phosphonium salt condensates are considered to withstand more than 50 launderings [40]. Since the washing of curtains is not frequent (15-20 times per lifetime), the recycling of FR curtains to FR insulation can be justified, as the FR treated cotton curtains still holds FR chemicals after disposal. The utilized FR in this study is N-methylol dimethylphosphonopropionamide (MDPA), an organophosphorus compound by Pyrovatex CP-new provided by Huntsman, was considered for the FR cotton curtains.

Figure 3 presents the graphical overview of the system boundaries which have been considered in the study. The analysis of the FR cotton curtains was conducted from "cradle to grave," *i.e.*, from raw material of FR input to the cotton fabric production, including FR finishing and up to disposal to incineration after usage. The functional unit was set to one set of FR cotton curtains (1 kg) in the usage stage, which took place in Italy. The choice of the functional unit of FR textile in kilograms is a logical choice from a production point of view; consequently, the environmental pressure of processes (spinning, weaving and finishing) and materials involved are functions of kilograms [41]. The same functional unit for recycled FR insulation as an alternate end-of-life for FR curtains was considered. However, some aspects were not included in case of unrealistic outcomes, such as the distribution to final customers, the end-of-life of FR curtains being 10 years, being washed 15–20 times (decided by semi-structured interviews), *etc.* It is assumed that FR curtains are disposed to waste incinerators, where heat and electricity are produced as byproducts. Unusually, the emissions from incineration are considered on the basis of fiber chemical composition. While the incineration of cotton is considered CO_2-neutral, the cotton crop absorbs the same amount of CO_2 and is released during incineration [26]. The environmental impacts, for instance, the carbon footprint of FR cotton curtains that is directly disposed by incineration or subjected to an alternative mechanical recycling, was followed by a life cycle assessment under EN ISO 14040:2006 [42] with the help of the GaBi software (Education version), and the carbon footprint is discussed elsewhere [43].

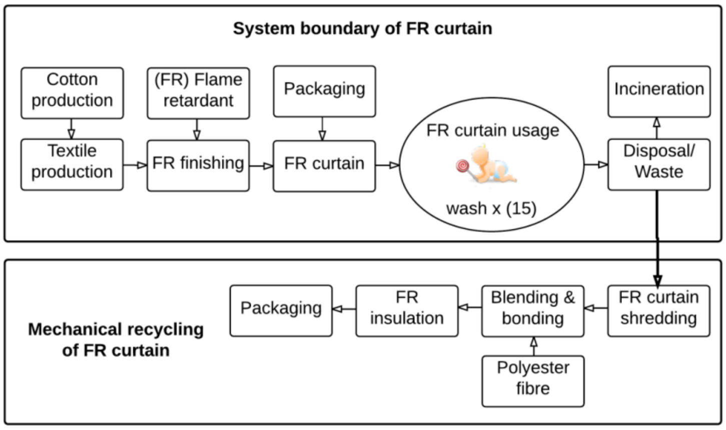

Figure 3. The process map used for carbon emissions from the virgin production of FR curtains and recycled FR insulation.

3. Results and Discussion

It is well-known that the environmental benefits of recycling are overseen, as the environmental issues associated with the manufacturing of new products can be avoided. Benefits of recycling are optimal due to the circumvention of disposal or wastes, provided that the environmental impacts are higher in virgin manufacturing than those of the recycling processes. To imply the mechanical recycling of FR textiles is an approach to acquire similar environmental benefits.

The potential carbon footprint for the production and use phase per FR curtains amounts to around 12 kg of CO_2 per lifetime, including 15 washes (10 years), without being disposed to an incinerator. In the life cycle of FR curtains, it is the production phase of cotton fabric that stands out in the main carbon footprint from Figure 4. The second prime carbon emission phase is the curtain manufacturing, which is subjugated via cutting and sewing. The FR finishes on the fabric (pad-dry-cure) also require continuous heating and drying, which contributes to emissions. The end-of-life of cotton curtains is presumed to be an environmental benefit, as the heat recovery from the incineration of cotton curtains is subjected to the generation of heat production and electricity.

Textile industry is considered one of the most complicated productive processes among any manufacturing system, which can possibly be distinguished into two major processes: mechanical, which includes spinning and weaving, and chemical, consisting of washing, dyeing, and finishing [44]. As can be seen in the flow chart (Figure 3), the produced cotton fibers are directed to a textile production process that requires electrical and thermal energy at spinning and weaving processes. The wet processing is also a part of textile production, which includes pre-treatment, bleaching, and dyeing. The FR is applied to cotton fabric by a conventional pad-dry-cure process. A considerable amount of energy is needed in all the steps. Indeed, the textile industry consumes an extensive amount of electrical and thermal energy [45]. It was assumed that all of the processes take place in Italy and the transportation was avoided. It was also assumed that energy is supplied by an Italian average-mix electrical supply, and thermal energy is supplied by natural gas in the GaBi software.

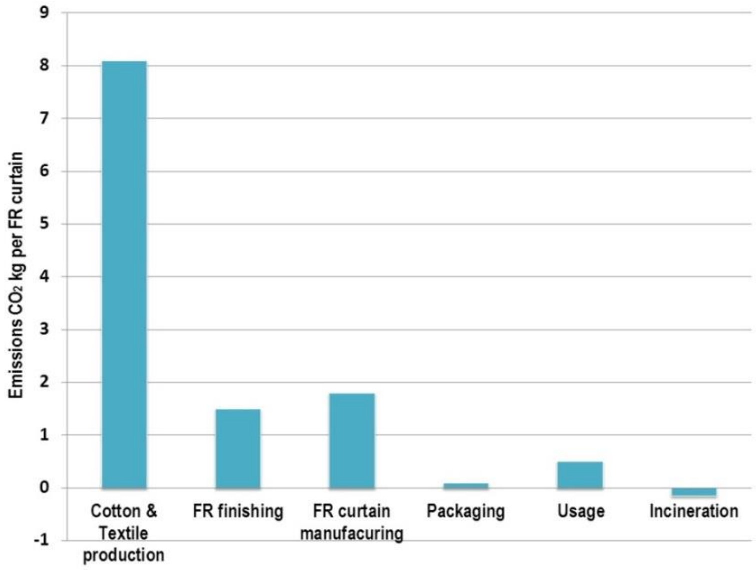

Figure 4. Carbon emissions by one kilogram of FR cotton curtains.

The results of the FR curtain manufacturing are directly dependent on the virgin production of cotton and textile product, which are the major contributors to the carbon footprint. The higher carbon emissions in FR cotton curtain production phase are also obvious; in cotton production, spinning is considered a primary energy-demanding process. Moreover, spinning and weaving processes have demonstrated higher energy consumption during the production of cotton fabrics and increase environmental burden [41].

Existing recycling technology for textile products is to produce low-grade products. Textile waste being a non-homogeneous material is difficult to sort according to different fabrics per item, dyes, and fiber types. Similarly, FR cotton curtains contain various accessories, such as dyes, FR chemicals, metal eyes for hanging rod, laces, and other decorative materials. However, for the mechanical recycling of FR curtains, only the fabric was considered for recycling after disposal. Figure 5 shows the results in kg of CO_2 emissions per kg of FR cotton/polyester insulation from FR cotton curtains. The process of producing polyester and blending/bonding of recycled cotton material (FR curtain) and virgin material (polyester fibers) has a considerable role in the results of CO_2 emissions. At blending/bonding stage, continuous layers of the web were formed from the shredding of FR curtains and polyester fibers prior to thermal bonding. The blending and bonding of FR insulation were carried out by consecutive webs on top of each other. For the bonding of fibers, the FR cotton and polyester webs thus carried through the heated bonding oven. The energy-extensive and multipart processes tend to produce high CO_2 emissions.

From Figures 6 and 7 the percentage breakdown of CO_2 emissions can be seen. The production phase of cotton curtains predominately emits more CO_2 emissions than other processes involved (Figure 6), whereas, in producing FR insulation, blending and bonding processes emit higher CO_2, followed by the fiber production (Figure 7). As mentioned above, the production phase is linked to extensive energy consumption and consequently contributes to higher CO_2 emissions. The raw material in the case of FR curtains, the cotton production includes various processes, such as ginning, spinning, roving, cone packaging, *etc.* Similarly, textile production includes different procedures, such as warping, spinning, weaving, finishing, *etc.*, whereas, in FR insulation, the raw material polyester fibers independently contribute to higher CO_2 emissions as compared to raw cotton. In addition, the polyester fibers have been shown to consume more energy than cotton [23]. Consequently, the production phase of polyester fibers contributes four times more to carbon emissions by utilizing 10 times more energy than cotton [46].

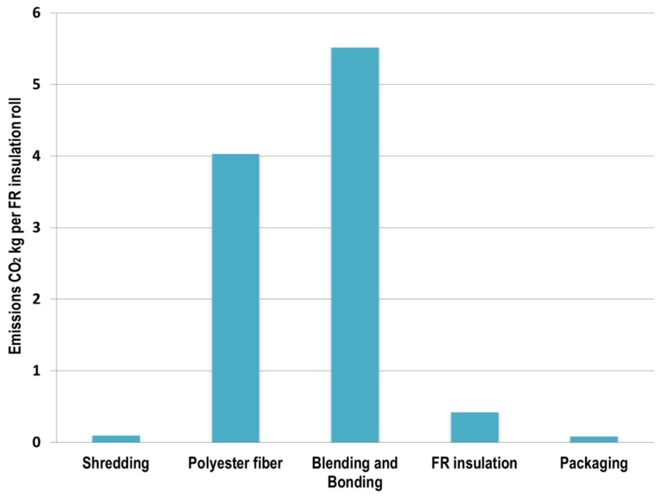

Figure 5. Carbon emissions by one kilogram of FR cotton/polyester insulation.

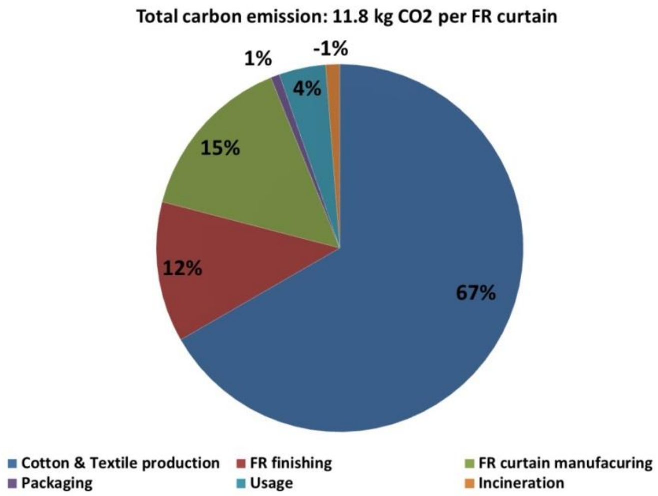

Figure 6. The percentage breakdown of carbon emissions by one kilogram of FR cotton curtains.

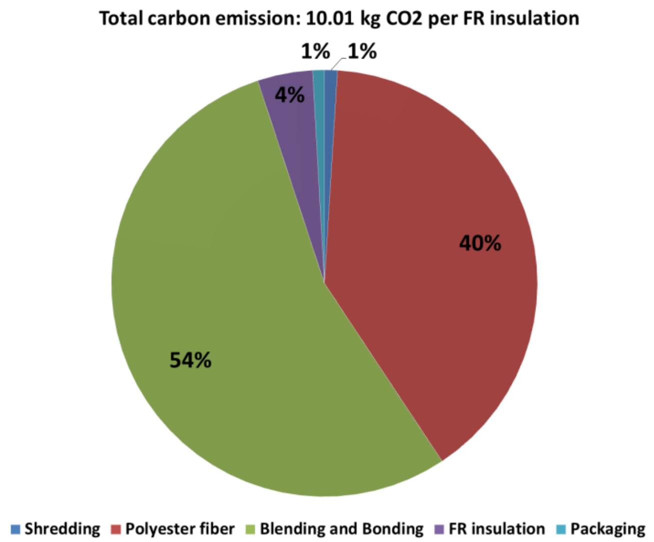

Figure 7. The percentage breakdown of carbon emissions by one kilogram of FR cotton/polyester insulation.

One can note that one kg of FR cotton/polyester insulation produces a similar carbon footprint (10.01 kg of CO_2) as compared to one kg FR cotton curtains (11.8 kg of CO_2). However, the overall carbon footprint can be reduced by 12.2 kg through saving the production of virgin cotton fibers and FR applications. The overall carbon footprint would be 22.21 kg for FR cotton/polyester insulation if the virgin production of FR cotton fibers is considered.

Sensitivity Analysis

A sensitivity analysis is provided for an effective representation and possible flaws in the system boundary or process flow charts. Primarily, the carbon emissions calculation for FR insulation manufacturing are made with the purpose of providing an alternate disposal of FR curtains through reduction in carbon footprint by avoiding virgin production. Moreover, in both process flow charts, transportation, retail, and distribution are evaded, nor is the use phase of FR insulation included in the system boundary. In the use phase of the FR curtain, user exposure to FR chemicals through skin contact and possible oral consumption by hand-to-mouth or inhalation are not included in the study. However, the atmospheric presence of chemicals from textiles in use phase raises concerns for mutagenic, carcinogenic, and reproduction toxic contents and is discussed elsewhere [47].

4. Conclusions

Even though a number of assumptions were made due to the lack of available data regarding energy usage within the processes of FR cotton/polyester insulation and FR curtain production, a great reduction in carbon footprint is obvious when virgin production is avoided. Although the calculated values of carbon emissions are incomplete, the analysis of mechanical recycling of FR cotton curtains has been successful in highlighting the significant amount of CO_2 released at different stages of production.

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