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Estimating the impact of the mattress fire safety Standard 16 CFR Part 1633 on bed fire outcomes

Stanley W. Gilbert[1] | David T. Butry[1] | Rick D. Davis[2] | Richard G. Gann[2]

[1]Office of Applied Economics, Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland

[2]Fire Research Division, Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland

Correspondence
Richard G. Gann, 9409 Eagleton Lane, Montgomery Village, MD 20899.
Email: rggann44@verizon.net

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Summary

Beds are a prevalent combustible in fatal fires in the United States effective 1 July 2007, the US Consumer Product Safety Commission promulgated a standard to severely reduce the heat release rate and the early heat output from mattresses and foundations when ignited by a flaming ignition source. This study estimates the Standard's success over its first decade using fire incidence, US population, and mattress sales data. The technique mitigates the influence of some exogenous factors that might have changed during this decade. The Standard is accomplishing its purpose, preventing approximately 65 fatalities (out of an estimated 95 fatalities in 2002-2005) from bed fires annually during 2015-2016, although not all pre-Standard mattresses had yet been replaced. Compared to residential upholstered furniture fires, which were not affected by the Standard, the numbers of bed fires decreased by 12%, injuries by 34%, and deaths by 82% between 2005-2006 and 2015-2016. Per bed fire, injuries decreased by 25% and fatalities decreased by 67%, indicating that the severity of bed fires is being reduced.

KEYWORDS

16 CFR Part 1633, bed fires, fire data, fire deaths, fire injuries, mattress fires

1 | INTRODUCTION

Effective 1 July 2007, the Consumer Product Safety Commission (CPSC) promulgated a standard for mattress flammability for flaming ignitions, 16 CFR Part 1633. This paper summarizes a methodology for quantifying the effects of this standard on the number of reported bed fires in residential structures and the numbers of associated occupant deaths and injuries. We then use this methodology to calculate changes in the losses from bed fires between 2005-2006, the last 2 years before compliant mattresses were mandated, and 2015-2016, the most recent 2 years when national fires losses were available. This methodology can be extended to future years as additional fire incidence data become available.

Beds have historically been one of the two most prevalent combustibles in fatal residential fires in the United States (residential upholstered furniture, RUF, being the other).[1] A bed typically consists of a mattress, a foundation, and an assembly of covers and pillows (collectively referred to as "bedding" or "bedding sets"). Typically, the bedding surrounds the mattress and comprises the initial ignition sites.

A person who is in the bed at the time of ignition is at risk from the smoke and flames even when the fire is confined to the bed itself. Then, as the fire grows, it can ignite nearby furnishings and raise the temperature throughout the room to untenable levels. The fire can also lead to room flashover, at which time all combustibles in the room are aflame and the hot and toxic combustion products flow rapidly into adjacent compartments. These combustion products threaten people throughout the residence.

To mitigate these losses, the CPSC enforces two fire safety standards for mattresses. Both involve testing of full mattresses. There are no standard tests or regulatory requirements for the flammability of bedding sets.

The first CPSC standard, 16 CFR Part 1632,[2] was originally issued in 1972 by the US Department of Commerce, with jurisdiction

transferred to the CPSC in 1973 by Federal statute. This standard is directed at reducing the number of ignitions due to cigarettes. In the test method, nine lit cigarettes are placed at prescribed locations along the top surface of the bare mattress or mattress pad. The same number of lit cigarettes are placed with sheeting between the cigarette and the mattress and on top of the cigarette. Ignition is determined by whether the mattress chars at least 2 in. (51 mm) away from a cigarette. Essentially all mattresses in use today met this standard.

The second CPSC standard, 16 CFR Part 1633, had an effective date of 1 July 2007.[3] The intent is to limit the rate and extent of fire growth, that is, minimize the probability of or delay flashover, when a mattress is ignited by a flaming source.[4] In what follows, "the Standard" refers to the open flame mattress standard.

In the Standard's test method, a bare mattress (on a foundation such as a box spring) is subjected to the flames from twin burners, which are directed at the top and side of the mattress, as shown in Figure 1. The top burner is 30.5 cm long. It imposes a heat flux of approximately 73 kW/m^2 along the top of the mattress for 70 seconds. The side burner simultaneously imposes a heat flux of approximately 55 kW/m^2 along the side of the mattress and foundation for 50 seconds. The twin burners simulate, in a repeatable manner needed for regulatory testing, the thermal threat to the mattress from burning bedding. The intensity, location, and duration of these flames were derived from the flaming behavior of various bedding sets.[5]

The peak heat release rate (PHRR) of the test specimen in 16 CFR Part 1633 must not exceed 200 kW during the 30-minute test. The peak occurs well after the burners have been turned off. For reference, prior to the Standard, the PHRR of a typical twin mattress/foundation set was approximately 2 MW, with king mattress/foundation sets achieving approximately twice that rate. The PHRR of a bedding set can reach 200 kW to 400 kW.[5] A PHRR of 1 MW can result in flashover in a bedroom of modest size. In addition, the Standard requires that the total heat released (THR) during the first 10 minutes of the test must not exceed 15 MJ.[3] The PHRR criterion was deemed to provide substantial opportunity for able occupants to discover the fire and escape. The THR criterion further reduces the hazard in the early stages of a bed fire.

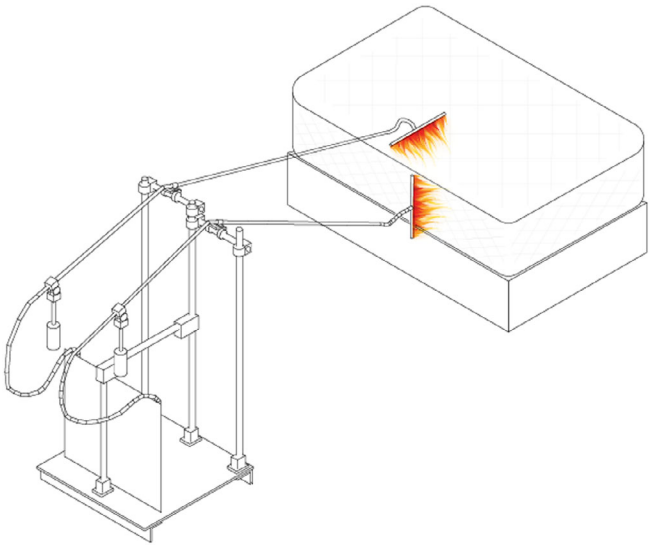

FIGURE 1 Schematic of a mattress and foundation exposed to the twin burners in 16 CFR Part 1633

Prior to the implementation of the Standard, between 2002 and 2005, mattresses and bedding were reported to be the first items to ignite in 11 500 residential fires attended by the fire service annually.[6] These fires resulted in 380 deaths, 1400 injuries and $360 million in direct property loss annually.[1] While only 3% of the home fires, mattress and bedding fires resulted in 13% of the fatalities, 10% of the injuries and 6% of the property loss. Mattress and bedding fires ignited by all flaming sources led to an estimated 95 fatalities and 570 injuries annually. Seventy-two percent of the fatalities from bed fires started by lighters, candles, and matches and 86% of the fatalities from bed fires started by smoking materials were in the area of fire origin when the fatal injury occurred.

There have been very few reported studies of the effect of a fire safety standard other than those that simply compare the numbers of fires, casualties, and property loss from CPSC or National Fire Protection Association (NFPA) publications. Perhaps the most examined legislation was the set of essentially identical State-by-State regulations of the ignition propensity of cigarettes.[7] Comparison of the fire fatalities from cigarette-initiated fires in the State of New York showed a reduction of ca. 40% between the average of the 7 years prior to the Rule and the average of the 5 years after its implementation.[8] Three analytical studies also obtained their data from the National Fire Incident Reporting System (NFIRS) database.[9] Hall found a 30% reduction in US fire deaths from all cigarette-initiated fires between 2003 and 2011.[10] Alpert and co-workers found that the Massachusetts law decreased the likelihood of residential fires caused by cigarettes by 28% between 2004 and 2010.[11] Since Massachusetts experienced a relative low number of fire deaths, they assumed that the reduction in deaths followed the reduction in the number of fires. Butry and Thomas found a 45% reduction nationally in cigarette-initiated RUF fires and a 23% reduction in deaths from those fires between 2002 and 2011.[12] Each of these used the NFIRS database, but with differing methods of analysis. The three studies found a reduction in fire fatalities centered on approximately 30%, and the variation among these findings provides a (non-rigorous) indication of the combined precision of the database and the analytical methods. Yau and Marshall found a 20% reduction in US cigarette-ignited fire deaths between 2000 and 2010, with some State-to-State variation.[13] Their analysis was based on mortality data from the National Center for Health Statistics, with a noted limit to their results since most States implemented their legislation during or after 2009.

This paper continues with an overview of the data sets used in Section 2 and a description of the analytical methodology in Section 3. Section 4 presents the modeling results. Section 5 provides discussion and implications; and Section 6 offers conclusions. More details on the calculations and findings can be found in Reference 14.

2 | INPUT DATA

Three sources of data were used in the analyses in this paper: NFIRS, the US Census, and the International Sleep Products Association (ISPA), the trade association for the mattress industry.

The NFIRS data provide incident-level information of reported fires nationwide, as provided by fire department personnel.[9] Though fire department participation is voluntary, approximately 80% of the US fire departments respond in any given year. The system is maintained by the US Department of Homeland Security's Fire Administration.

The NFIRS system compiles records of the time, date and location of all reported incidents; the type of the incident (eg, fire, emergency medical service call, hazardous materials incident); property use; equipment and personnel on the call; the number, type and severity of casualties; actions taken; and a host of other data. For fires specifically, NFIRS collects information on the extent of the fire, room of origin, heat source, item first ignited, human and other factors contributing to ignition, item principally contributing to fire growth, and presence and effectiveness of detection and automatic suppression equipment, among other data. While NFIRS has known reporting limitations, it is still the most comprehensive data set available for understanding the nature and extent of the urban fire problem in the United States.

This study includes residential (both single-family and multi-family) fires reported in NFIRS between 2005 and 2016. Since NFIRS is a voluntary system, sometimes new fire departments contribute to the system and participating departments drop out. To ensure that results are not an artifact of fire departments entering and leaving the system, only fires from departments that reported fires during both the periods 2005-2006 and 2015-2016 are included. We averaged these bounding two-year periods to mitigate the influence of any unusual one-year fire data, without obscuring any trends in a mattress replacement process that was still evolving.

The US Census is a decennial compilation of data about the American people and economy.[15] This study uses the US Census population projections for the years from 2010 to the present, and intercensal estimates for the years before 2010. The population of the United States grew from approximately 299 million in 2005 to approximately 326 million in 2016.

The International Sleep Products Association (ISPA) supplied sales data, denominated in both dollars and units, for the four US sales regions (Northeast, West, Midwest, and South) for the years from 2000 to 2018. Sales slowed during the recent recession but have now returned to pre-recession levels. The CPSC estimated that there were between 237 million and 304 million mattresses in US residences in 2005.[3]

On average, the original purchaser of a mattress replaces it roughly 10 years later.[16] A used mattress may be resold, passed on to another user, or discarded. Thus, the total useful life of a mattress is difficult to estimate, but might well be considerably longer than a decade.

3 | STRUCTURE OF THE ANALYSIS

3.1 | General structure

The main objective was to capture the "big picture" results of the implementation of the Standard, that is, the changes in the numbers of fires, injuries, and deaths from bed fires between the years before the compliant products entered use and today. The technique used to obtain these results can then be extended to future years as additional fire incidence data become available.

We were not sure a priori of the size of any change or whether it would be discernible. We were also aware that, during the decade of interest, many factors other than the implementation of the Standard might have affected the outcome of fires in general and bed fires in particular. Thus, from the start, we designed the analytic process to obtain meaningful results in a world that was not necessarily in steady state.

To do this, we constructed a number of statistical models, each with a different:

- approach to separating the effect of exogenous (non-fire) factors on the fire outcome,
- method of analysis for obtaining the change in fire outcome in the final year of the decade of interest,
- grouping of fire incidents by ignition source and time of day the fire occurred,
- role of the combustibles in the fire report, and
- representation of the replacement of pre-Standard mattresses.

For each model, we performed calculations to determine the numbers of each of five fire *outcomes* that are entries in the NFIRS reports of fire incidents:

- bed fires,
- bed fires that spread beyond the object of origin,
- bed fires that spread beyond the room of origin,
- injuries, and
- fatalities.

In all, we calculated the impact of the Standard using 544 different models. The following sections contain further explanation of the modeling. Mathematical details can be found in Reference 14.

3.2 | Approaches

It is possible that external factors (eg, the prevalence of working smoke alarms, style of building construction, and nature of home occupancy) might have changed over the decade of interest. These changes might confound the statistically determined effect of the Standard on the fire outcomes, not all the factors might be known, and the contribution of each of these factors to fire severity might be difficult to quantify.

Thus, this study examined four different *approaches* to normalizing, or indexing, the bed fire severity results to limit the potential impact from these factors.

- The *RUF-controlled Approach* uses residential upholstered furniture (RUF) fires as a control group for bed fires. For example, we calculate the ratio of the number of fatalities from a particular subset of bed fires (eg, those started by flaming ignitions) to the number of fatalities from the same subset of RUF fires and observe the change in that ratio between 2005-2006 and 2015-2016. The assumption of the RUF-controlled Approach is that, except for the Standard, the same factors (such as usage of candles in homes or cigarette ignition strength) that affect the numbers of bed fires, deaths, and injuries affect the outcome of RUF fires in a similar manner. Thus, in the absence of the Standard, the ratios of bed-to-RUF fires, fatalities, and injuries would remain constant over time.
- Analogous to the RUF-controlled Approach, the *All-fire-controlled Approach* indexes bed fires to all residential structure fires. This approach assumes exogenous factors that influence the reported occurrence of bed fires affect all other residential fires in the same way. In the absence of the Standard, the ratios of bed-to-all fires, fatalities, and injuries would remain constant over time.
- The *Variable-fire-department Approach* is similar to the RUF-controlled Approach, in that it indexes bed fires to RUF fires, but differs in allowing the initial ratio of bed fires to RUF fires to reflect the annual reports from each fire department. The effect of the Standard is assumed to be constant across the United States. In the absence of the Standard, within a fire department's jurisdiction, the ratios of bed-to-RUF fires, fatalities, and injuries would remain constant over time.
- The *Per-bed-fire Approach* differs from the other three approaches in that it directly indicates any changes in the *severity* of bed fires as a result of the Standard. The fire outcomes were limited to injuries and fatalities. Two versions of this Approach were used: (a) allowing the initial ratio of bed fire outcomes to bed fires to vary by fire department and (b) assuming the initial ratio of bed fire outcomes to bed fires to be constant for all fire departments.

3.3 | Methods of mattress replacement analysis

For each approach, we performed two *methods* of analyses. A *before-and-after* analysis was used to examine whether there has been a statistically significant change between the pre-Standard outcomes (2005-2006, the two full years prior to the effective date of the Standard) and the post-Standard outcomes (2015-2016, the two most recent years in the NFIRS database).

The *mattress replacement* method used annual mattress sales data[16] to model the rate of Standard-compliant mattress penetration into homes each year. These incremental annual outcomes are then summed to obtain the outcome in the last year.

All of the models assume that bed fires are independent events occurring at a constant rate within a given time interval, that is, within 1 year or over the entire decade.

3.4 | Rates of mattress replacement

Within the mattress replacement method, we used two alternative *representations* of the replacement of pre-Standard mattresses by post-Standard mattresses. In the *first-in-first-out* (FIFO) representation, the oldest mattresses are replaced first. In the *random replacement* or equal-probability (EP) representation, each mattress in service is equally likely to be replaced regardless of age. Each case was evaluated for the upper or lower CPSC estimates of the initial number of mattresses in residences.

Using the annual mattress sales data for the years in between the "before" and "after" fire data, and taking into account population change during that time period, enables estimation of the rate of penetration of new mattresses into homes. This, in turn, allows estimation of whether any changes in fires and fire outcomes follow the usage of the Standard-compliant mattresses.

These methods inherently assume that there is a constant number of mattresses per person in the country over the period of the study. Thus, as the population grows, there is a proportionate increase in the number of mattresses.

Figure 2 shows the estimates of standard-compliant mattress penetration over time in the United States for the two replacement methods and the high and low estimates of the number of mattresses in the United States in 2005. Holding the replacement method constant, the smaller initial number of mattresses produces the more aggressive replacement schedules. For longer periods of time, the FIFO methods produce the more aggressive replacement schedules.

The CPSC staff recognized[3] that some manufacturers were shipping/selling compliant mattresses before 15 March 2006, or 15 months before the effective date of the Standard. Figure 1 suggests that these sales represent an upper limit of about 10% of the mattresses in use on the effective date of the Standard. The before-and-after method neglected this fraction, but the replacement method accounted for it.

Note that these are not the high and low extreme models for the rate of mattress replacement, but they are tractable and have some logical basis. Other types of models might include some households replacing the adult mattresses frequently, for example, every 5 or 7 years, and the children's mattresses once after each child graduates from a crib, or a different replacement profile for second-hand mattresses. There are no data that would allow these kinds of individual-choice-based concepts to be incorporated here.

3.5 | Fire incidents and reported roles of combustibles

For each of the four approaches, we considered 16 residential fire scenarios.

- Four groupings of *fire incidents*:

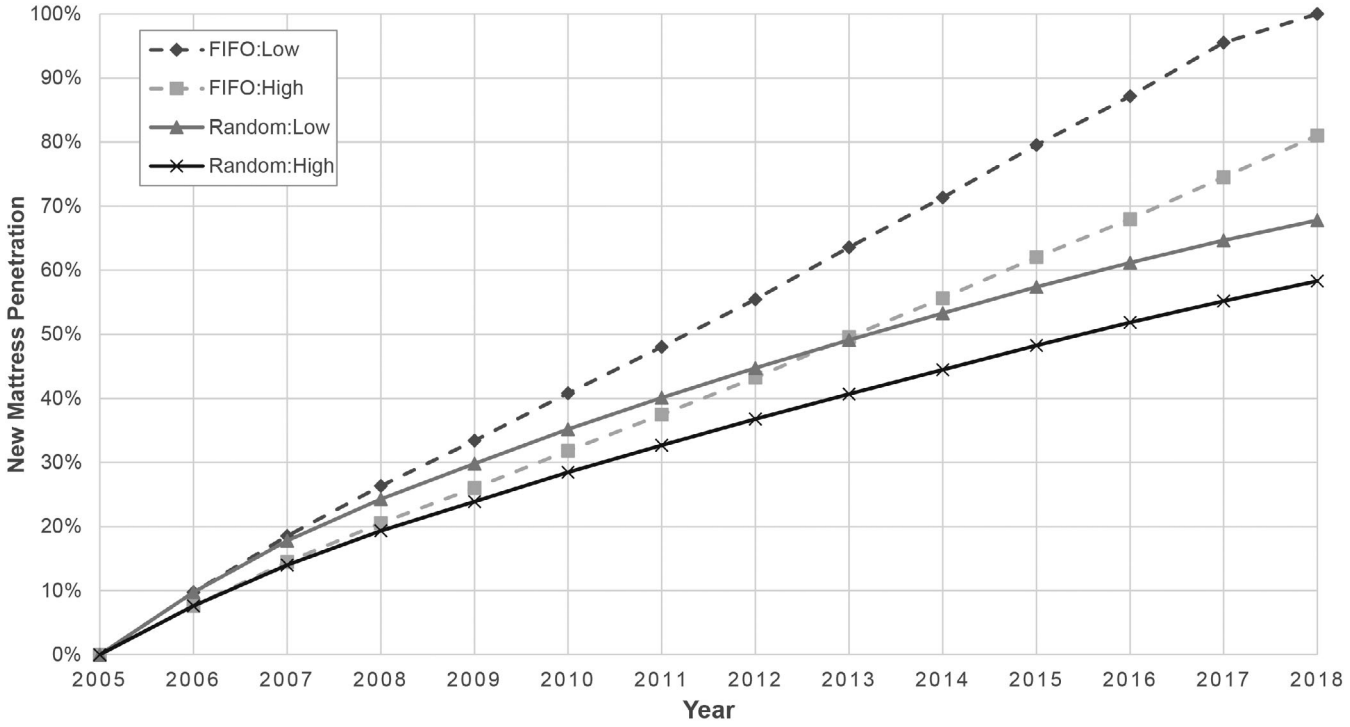

FIGURE 2 New mattress penetration in the United States during the years 2005 to 2018 for four penetration representations

1. All bed or control fires started by flaming ignition sources;
2. All bed or control fires started by smoking materials;
3. All bed or control fires that occurred at night, regardless of ignition source, and
4. All bed or control fires, regardless of ignition source and time of day.[1]

- For each of these groupings, we considered four *roles* of bed combustibles in the fire.

1. Bed fires in which a mattress was identified as the item first ignited;
2. Bed fires meeting Role 1, but expanded to include bed fires in which bedding was identified as the item first ignited;
3. Bed fires meeting Role 1, but expanded to include fires in which a mattress was identified as the item most contributing to flame spread; and
4. Bed fires meeting Role 3, but expanded to include bed fires in which bedding was identified as the item most contributing to flame spread.

Often, "item most contributing to flame spread" is not reported in the reports in NFIRS, for example, when it is the same as the item first ignited. If that field is blank for an incident, then the incident will not be added to the analysis based on the "item most contributing to flame spread" field. However, it may still be included based on the content of the "item first ignited" field.

It seems likely that in nearly all flaming pre-Standard bed fires, the bedding was ignited first and the mattress was the item most contributing to fire growth. Coding these roles is optional in the NFIRS fire incident reports. Including these roles in our overall analysis provides a robustness check to ensure that our results are not a product of how we defined the role of bed combustibles.

None of the models include an explicit rendition of changes in the nature or flammability of bedding sets, since there is no sound basis for one. There are an immense number of combinations of the components, there are no sales data for the components, and there is no information on the bedding in the fire incident reports. Thus, any systematic trend in the flammability of bedding sets over time is a confounding factor that might affect the balance among the roles of combustibles described above.

3.6 | Fire outcomes

As listed in Section 3.1, the impact of the Standard was evaluated across five fire *outcomes* that are entries in the NFIRS reports of fire incidents: the numbers of bed fires, bed fires that spread beyond the object of origin, bed fires that spread beyond the room of origin, injuries resulting from bed fires, and fatalities resulting from bed fires.

With regard to the second and third outcomes, the spread of a bed fire to other combustibles beyond the bed and to other spaces

can only occur if the bed fire is flaming. A smoldering fire will not ignite a second item unless it is in intimate contact with the bed, and the heat release rate from a smoldering fire is far too low to initiate room flashover. However, under the right circumstances, the smoldering fire could transition into a flaming fire. If so, the Standard might reduce the intensity of the flaming and thus reduce the losses from, for example, cigarette-initiated fires as well as those fires started by flaming ignition sources.

We assumed that there are no degrees of fire performance improvement of a mattress. Otherwise worded, the required PHRR and the early THR of post-Standard mattress are so low that differences among compliant mattress designs do not affect the fire outcome.

3.7 | Impact of the Standard

The impact of the Standard is characterized by the change between the indexed number of bed fire outcomes after imposition of the Standard to the indexed number of the same bed fire outcome before imposition of the Standard. The impact from a before-and-after analysis is denoted by δ, for example:

$$\delta = \frac{\frac{\text{Bed fires after}}{\text{Control fires after}}}{\frac{\text{Bed fires before}}{\text{Control fires before}}}.$$

We are interested in the case where $\delta < 1$ or $\ln(\delta) < 0$, which would indicate that the (undesirable) outcomes after the imposition of the Standard are fewer than before imposition of the Standard. $\ln(\delta)$ is what is actually used for analysis and reporting because $\ln(\delta)$ is easier to estimate than δ, and because it is easier to test for the statistical significance of $\ln(\delta) < 0$ than of $\delta < 1$.

The right-hand side of the equation for the impact from a mattress replacement analysis is the same. However, the impact is denoted as ψ. This differs from δ in that the value of δ is a characteristic of the time period analyzed (and thus would change if the time period used as the "after" year changed), while ψ is a characteristic of the difference in the mattresses' change in fire contribution. At a time when essentially all the pre-Standard mattresses have been retired, δ and ψ will converge.

3.8 | Uncertainty

There is a degree of uncertainty in each of the simulations, and the SEs were calculated throughout. Many of the outcomes were identified as not statistically significant, generally due to the small number of fire incidents in those simulations.

SEs were determined in different ways depending on the estimation methodology used. For any model estimated using maximum likelihood or as a generalized linear model (GLM), the SEs were determined in the usual way for those estimation methods.[17] For models estimated using Bayesian Markov-Chain Monte Carlo (MCMC) methods, 15 000 iterations (after warmup) were run, and the SE was the SD of the results over those iterations.[18] The following shows the estimation method for each type of model. BA denotes the Before-and-after Method and MR denotes the Mattress Replacement Method.

• Index: All Fires	BA: Maximum Likelihood	MR: Maximum Likelihood
• Index: Variable Fire Dept	BA: Bayesian MCMC	MR: Bayesian MCMC

4 | RESULTS

4.1 | Overview tables

The following four tables show the output of the "big picture" models. The figures of merit, δ and ψ, are the indexed changes in fire outcome in 2015 to 2016 relative to a baseline in 2005 to 2006. They are as defined in Section 3.7. η is the ratio of the number of the pre-Standard bed fire outcomes in the column heading to the number of the same outcome from control fires before the Standard.

In each of the tables, the first data row contains the calculated values of $\ln(\eta)$. Positive estimates indicate more bed fire outcomes than the control in 2005 to 2006, while negative estimates indicate fewer than the control in those years. The second row contains the SEs in these calculations.

The third and fourth data rows contain the calculated values of and SEs in $\ln(\delta$ or $\psi)$. Large negative values of $\ln(\delta)$ or $\ln(\psi)$ indicate that the Standard has reduced the undesirable fire outcomes. Large positive values of $\ln(\delta)$ or $\ln(\psi)$ indicate that the (undesirable) fire outcomes increased after the imposition of the Standard. The 95% confidence intervals were calculated as 1.9 times the SEs.

Table 1 shows how the Standard changed the outcome profile of bed fires relative to the profile of the unaffected RUF fires. Table 2 shows how the severity of bed fires was changed by the Standard. Results are only shown for injuries and fatalities because the fires ratios are unity. Table 3 is similar to Table 1, but is a check on the sensitivity of the models to whether the incremental annual changes in fire outcome are summed or whether the entire decade is calculated as a single time step. Table 4 is similar to Table 2, but with the same use of annual time steps as in Table 3.

As the models become more complex, and especially as the fire incidence data are divided into smaller groupings, the SEs can become comparable to the mean values for $\ln(\delta)$ or $\ln(\psi)$. In these cases, it may not be possible to determine whether the Standard had a beneficial effect, a negative effect, or no effect. The values of $\ln(\delta)$ or $\ln(\psi)$ and the values of $\ln(\eta)$ that are statistically significant at the 95% confidence level (two-sided) are in ***boldface italics***.

TABLE 1 Impact of the Standard on bed fires, injuries, and fatalities, estimated using the RUF-controlled approach with the before-and-after replacement method

	Fires			Injuries			Fatalities		
Ignition type	Flaming	Smoking	All	Flaming	Smoking	All	Flaming	Smoking	All
ln(η)	***0.78***	***0.23***	***0.38***	***0.65***	−0.10	***0.18***	0.06	***−0.36***	***−0.26***
SE	0.03	0.03	0.02	0.08	0.07	0.04	0.24	0.15	0.10
ln(δ)	***−0.12***	0.01	0.01	***−0.41***	0.12	−0.07	***−1.73***	−0.002	−0.15
SE	0.05	0.06	0.03	0.13	0.12	0.06	0.51	0.24	0.15
Change in δ (%)	***−12***	1	1	***−34***	13	−7	***−82***	−0.2	−14
Conf. interval	***−19:−3***	−10:13	−4:6	***−49:−15***	−11:44	−18:5	***−93:−52***	−37:58	−35:15

TABLE 2 Impact of the Standard on bed fire injuries, and fatalities using the per-bed-fire approach with the before-and-after replacement method

	Injuries			Fatalities		
Ignition type	Flaming	Smoking	All	Flaming	Smoking	All
ln(η)	***−2.80***	***−2.01***	***−2.56***	***−4.77***	***−4.34***	***−6.32***
SE	0.11	0.09	0.06	0.19	0.29	0.48
ln(δ)	***−0.29***	0.16	0.02	***−1.12***	0.21	0.16
SE	0.09	0.10	0.05	0.45	0.20	0.13
Change in δ (%)	***−25***	17	2	***−67***	23	17
Conf. interval	***−37:−10***	−3:41	−7:12	***−86:−22***	−17:82	−9:50

TABLE 3 Impact of the Standard on bed fires, injuries, and fatalities, estimated using the RUF-controlled approach with the FIFO mattress replacement method

	Fires			Injuries			Fatalities		
Ignition type	Flaming	Smoking	All	Flaming	Smoking	All	Flaming	Smoking	All
ln(η)	***0.80***	***0.19***	***0.38***	***0.76***	***−0.08***	***0.22***	0.25	***−0.40***	***−0.36***
SE	0.02	0.03	0.01	0.06	0.07	0.03	0.17	0.13	0.08
ln(ψ)	−0.08	0.08	0.02	−0.26	***0.32***	0.03	***−1.74***	0.15	−0.06
SE	0.05	0.06	0.03	0.15	0.12	0.07	0.77	0.25	0.15
Change in ψ (%)	−8	9	3	−23	***38***	3	***−83***	16	−6
Conf. interval	−16:2	−4:22	−4:8	−43:3	***9:74***	−10:18	***−96:−21***	−29:90	−30:26

TABLE 4 Impact of the Standard on bed fire injuries and fatalities, estimated using the per-bed-fire approach with the FIFO mattress replacement method

	Injuries			Fatalities		
Ignition type	Flaming	Smoking	All	Flaming	Smoking	All
ln(η)	***−1.86***	***−1.65***	***−1.93***	***−4.54***	***−3.24***	***−3.99***
SE	0.04	0.05	0.02	0.13	0.10	0.06
ln(ψ)	***−0.27***	***0.18***	−0.05	−0.63	0.16	0.04
SE	0.08	0.09	0.05	0.38	0.19	0.12
Change in ψ (%)	***−24***	***19***	−5	−46	18	4
Conf. interval	***−35:−11***	***0:43***	−14:5	−75:12	−19:70	−18:32

4.2 | Supplemental tables

Reference 14 contains an additional 34 tables in which we examined the substructure of the various models. In many of those tables, all the calculations of change in δ or ψ were statistically insignificant. This generally resulted from too-small data sets due to subdividing the data too finely. In Section 5 in this paper, we cite the numbers of those tables whose content identified useful insights into the effects of the Standard on the fire outcomes

5 | DISCUSSION

5.1 | Effect of the Standard on the outcomes of bed fires ignited by flaming sources

5.1.1 | Fatalities

Table 1 through Table 3 project a consistent image that the Standard has resulted in a 60% to 80% reduction in fatalities from bed fires initiated by a flaming source. The number of fatalities prevented by beds with Standard-compliant mattresses when ignited by flaming heat sources during the 2-year period 2015 and 2016 are estimated to have been 59 (95% CI: 22-122) using the before-and-after method and 75 (95% CI: 33-138) using the mattress replacement method.

Further calculations (Reference 14) indicate that this result is independent of whether the mattress or bedding is coded as the first item ignited or the item contributing most to flame spread. It is also independent of whether the bed fire outcomes are referenced to all fires, whether the Nations' fire departments are treated as a single entity or as individual units, and how the mattress replacement process was simulated. There is also a decrease in the number of fatalities per bed fire.

This finding is not surprising, since the test method was derived from full-scale experiments[6] and the performance criteria were based on realistic fire hazard calculations.[3,4]

In Table 4, the subdivision of the data by years resulted in cells with too few entries and the uncertainty became comparable to the mean value. This also appears in some of the supplemental calculations.

Nighttime fatalities decreased significantly relative to all fires (Tables 21 and 26 in Reference 14). For the calculations relative to RUF fires, no significant change could be quantified since the SEs were comparable to the mean values.

The calculated reductions in fatalities are consistent with the fraction of mattresses that have been replaced. Figure 2 shows that, using the FIFO mattress replacement representation, 65% to 80% of mattresses in the United States should have been replaced by 2015; using the Random Replacement representation, 50% to 60% should have been replaced.

5.1.2 | Injuries

Tables 1, 2, and 4 show a consistent 35% reduction in injuries from bed fires initiated by a flaming source. No significant effect can be seen in Table 3, since the mean value and SE are both small numbers and comparable in magnitude. While the NFIRS reports code the severity of injuries, we chose not to analyze by severity because we expected that the resulting categories would have been too fine to produce significant results.

Further calculations (Reference 14) were hampered by large SEs in many cases, but the data that were significant indicate that the reduction in injuries is independent of whether the mattress or bedding is coded as the first item ignited or the item contributing most to flame spread. It is also independent of whether the bed fire outcomes are referenced to all fires, whether the Nations' fire departments are treated as a single entity or as individual units, and how the mattress replacement process was simulated.

Nighttime injuries decreased significantly relative to all fires (Tables 20 and 25 in Reference 14), but showed no such change relative to RUF fires due to the large SEs. We note that when indexed to all fires, the bed fires led to a very substantial *decrease* in nighttime injuries from fires coded as mattress or bedding as the ignited combustible (Tables 20 and 25 in Reference 14). When indexed to RUF fires, the bed fires led to an equally substantial *increase* in fires coded as mattress only (Table 10 in Reference 14).

5.1.3 | Reported fires

Tables 1and 3 show that the Standard resulted in at most a small decrease in the number of reported bed fires relative to any change in RUF fires. However, calculations relative to all fires show a significant 30% to 50% decrease in all ignition groups, including ignition by smoking materials. (See Tables 17 and 22 of Reference 14.) This decrease was not sensitive to what was recorded as the first item ignited or the item most contributing to flame spread, or the mode of mattress replacement in the model. The decrease was modestly greater when summing over annual increases in post-Standard mattresses than in before-and-after calculations.

The annual number of reported residential fires only decreased by approximately 8% between 2005-2006 and 2015-2016.[1] Thus, the calculated decrease in bed fires is real and not a result of there having been more fires overall. If the decrease in bed fires is attributed to the Standard, then there must have been a separate factor that coincidentally reduced the number of RUF fires to the same extent.

Otherwise, there must have been a factor other than the Standard that affected both types of soft furnishing fires. There are diverse possibilities, including a decrease in children playing with matches and cigarette lighters, a decreased use of candles in sleeping areas, a reduction in the flammability of the fabrics and/or padding materials used in both beds and RUF items, etc.

5.1.4 | Spread of fire beyond the room of fire origin

There was a 20% to 50% decrease in the flaming-initiated fires spreading beyond the fire room relative to all fires, consistent with the Standard mandating a substantial reduction in the heat release rate of the mattress. The decrease was toward the high end of this range for the mattress replacement calculation (Table 24 in Reference 14), compared to the before-and-after calculation (Table 19 in Reference 14).

5.1.5 | Spread of fire beyond the bed

The calculations show little evidence of a significant decrease in flame spread beyond the bed, whether relative to RUF fires or all fires. This suggests that many pre-Standard mattresses, combined with bedding, resulted in fatalities while the fire was localized. This is consistent with NPFA reporting that in 2002 to 2005, prior to the Standard, 72% of the fatalities from bed fires initiated by flaming sources were reported as occurring in the room of fire origin,[6] that is, in or near to the bed.

One set of all-fires-controlled calculations shows a 30% decrease for fires ignited by smoking materials and those ignitions occurring at night. However, this decrease is only seen for the mattress replacement calculation (Table 23 in Reference 14), and not the before-and-after calculation (Table 18 in Reference 14).

5.1.6 | Aggregation of results

We have created a hypothesis that combines the major features of the above results and discussion.

The Standard has resulted in a reduction in fatalities from bed fires ignited by flaming sources that is comparable to the fraction of pre-Standard mattresses that have been replaced by post-Standard mattresses.

- Prior to the Standard, some fraction of those fatalities occurred while the fire was still confined to the bed. These fatalities were reduced in number by the limited peak heat release rate and especially by the limited early total heat release from the post-Standard mattresses.
- Another fraction of the pre-Standard fatalities had occurred when the fire had grown beyond the bed but was still confined to the room of fire origin. The limited PHRR of the mattress resulted in fewer of these fires and thus fewer fatalities.
- The remainder of the pre-Standard fatalities had occurred from fires that extended beyond the room of fire origin. Since the limited PHRR of the mattress reduces the potential for room flashover, these fatalities should also have been reduced.

5.2 | Effect of the Standard on the outcomes of bed fires ignited by smoking materials

The test performance mandated in 16 CFR Part 1633 was not intended to affect ignition by smoking materials. However, we included this class in the modeling in case there were derivative benefits or costs that might have arisen, for example, due to the choice of materials in the post-Standard mattresses.

Table 1 through Table 4 do not show a statistically significant change in fatalities from bed fires started by smoking materials, in large part because of the large SE relative to the mean value. The supplemental Tables 11, 21, and 31 in Reference 14 show isolated significant decreases in fatalities for those cases where the mattress is recorded as the first item ignited.

There might be a 20% decrease in the fire spread beyond the bed and beyond the room relative to all fires. No effect was seen relative to RUF fires. If this is real, it suggests the presence of an exogenous factor that affects RUF and bed fires comparably, but is less effective on other types of fires.

There is no evidence that the Standard led to a change in the number of fires from smoldering ignition. This is not a surprise, since essentially all in-use mattresses had been manufactured in the more than 30 years between the promulgation of the cigarette ignition test, 16 CFR Part 1632, in 1972 and 2005. It also suggests that the ease of cigarette ignition of bedding items had not changed during the decade covered by this study relative to the ease of ignition of RUF items.

Tables 3 and 4 show bed fires being significant *more* likely to result in injuries. These two tables use the FIFO mattress replacement representation. Tables 10 and 37 in Reference 14, which are equivalent except for using the before-and-after representation, do not show this increase because the SEs are too large. Supplemental Tables 15, 35, and 39 in Reference 14 show this increase for all mattress replacement rates for the per-RUF-fire, per-all-fire, and per-bed-fire approaches, respectively. Because of this broad set of models, it is likely this is a real effect.

A likely explanation is that post-Standard mattresses experienced weaker flaming following any transition from smoldering, so some formerly fatal fires now only cause injuries. There are other possible contributors to this result, including:

- As the new mattresses were replacing the old ones, the fire hazard of the bedclothes might have been increasing;
- The cigarette used in the test for ignition resistance of mattresses might have been a weaker ignition source;[2]
- The pre-Standard mattresses might have provided an additional degree of protection from the consequences of cigarette ignition beyond that observed in the pass/fail test method and/or
- People might be more likely to fight the smaller fires, increasing their potential for injury.

In all, the Standard appears to have had no systematic effect on the risk of fatalities from smoldering fires. It is reasonable that some pre-Standard fatalities from smoldering fires that had transitioned to flaming now resulted in injuries instead.

6 | CONCLUSION

Effective 1 July 2007, the CPSC promulgated a Standard to severely reduce the allowed peak heat release rate (PHRR) and the early total heat release (THR) from mattresses and foundations that had been ignited by a flaming ignition source. The design and intensity of this ignition source replicated the flames from vigorously burning bedding. Mattresses complying with this Standard have been entering residences for more than a decade.

The purposes of this study were to (a) establish a methodology for evaluating the impact of this Standard and (b) estimate the extent to which the Standard was achieving its intent to date.

The results of the analyses show that the Standard is accomplishing its purpose. The beds with new mattresses are far less likely to lead to a fatal fire upon ignition by flaming ignition sources.

- Relative to RUF fires, which are not affected by the Standard, flaming ignitions of beds led to decreases in the numbers of fires by 12%, injuries by 34%, and deaths by 82% between 2005-2006 and 2015-2016.
- Injuries per bed fire decreased by 25% and fatalities decreased by 67%. The annual number of fatalities prevented in 2015-2016 was estimated as 65, a two-thirds decrease from the estimated 95 fatalities that occurred in 2002-2005.
- The reduction to date in casualties from flaming ignitions is comparable to the 50% to 80% of mattresses that have been replaced.

A unified hypothesis explains how the life savings were achieved.

- Prior to the Standard, some fraction of those fatalities occurred while the fire was still confined to the bed. These fatalities were reduced in number by the limited peak heat release rate (PHRR) and especially by the limited early THR from the post-Standard mattresses.
- Another fraction of the pre-Standard fatalities occurred when the fire had grown beyond the bed but was still confined to the room of fire origin. The limited PHRR of the mattress resulted in fewer of these fires and thus fewer fatalities.
- The remainder of the pre-Standard fatalities had occurred from fires that extended beyond the room of fire origin. Since the limited PHRR of the mattress reduces the potential for room flashover, these fatalities should also have been reduced.

Regarding fires with smoking materials as ignition sources, there was no significant change in reported fires or the fatalities from these fires over the decade covered in this paper. However, there was a significant *increase* in injuries per bed fire. This is consistent with post-Standard mattresses experiencing weaker flaming following any transition from smoldering, so some formerly fatal fires now only cause injuries.

Overall, the ensemble of calculations was robust. Normalizing the outcomes of bed fires to RUF fires or all residential fires generally isolated the effect of the Standard, although some subsets of the data indicate the presence of one or more additional, unidentified factors. There was no evidence that the decrease in fatalities was affected significantly by (a) the calculation of the introduction rate of post-Standard mattresses into residences, (b) the reported role of the mattress or bedding in fire initiation and growth, and (c) variability in fire reporting among fire departments,

Because of the rigor of the Standard and the mattress industry's success in selling products that are Standard-compliant, the prognosis for continued success is positive. Barring any other changes affecting the incidence of bed fires and their consequences, it is likely that the number of prevented fatalities from flame-ignited bed fires will continue or exceed the current level as more pre-Standard mattresses are replaced.

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DATA ACCESSIBILITY

The data and scripts used to generate the tables in Reference 14 can be accessed at https://doi.org/10.18434/mds2-2294

ORCID

Richard G. Gann https://orcid.org/0000-0002-4172-1328

ENDNOTES

[1] "Flaming" Ignition type includes all NFIRS ignition sources that apply a flame to the combustible. "Smoking" ignition type includes smoking materials as the only NFIRS descriptor of non-flaming ignition sources. Thus, the number of reported fires included in the "All" ignition type is larger than the sum of the two ignition types.

[2] The original test cigarette in 16 CFR Part 1632 was a commercial cigarette identified in 1972 as the most severe ignition source for testing mattresses and mattress pads. In 2008, the manufacturer of that cigarette announced that it would be stopping production of that cigarette. Starting then, testing might have been performed using the available commercial cigarettes, which were, by law, less likely to ignite upholstered furniture and mattresses. Effective October 23, 2012, the CPSC required the use of SRM 1196 cigarettes, which became available in 2020 and were designed to replicate the ignition strength of the original commercial cigarette.[19] Thus, for as much as half of the period under consideration in this report, the test cigarette used in 16 CFR Part 1632 might have been weaker than in the years preceding the effective date of the Standard.

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