Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
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doi: 10.3850/978-981-18-8071-1_P175-cd

A New Model for Fuel Transfer Leak Frequencies

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This paper presents a new model of the frequencies of leaks during the transfer of fuels between transport units and fixed installations. The model covers loading and unloading of bulk liquids and liquefied gases on marine, road and rail tankers through flexible hoses and articulated arms. It is based on a review of 35 sources containing original data on transfer leaks and associated activity. After evaluating the quality of each source, the model was based on a detailed analysis of six sources that had high quality ranking. These were used to develop a leak frequency model that takes account of site-specific operational characteristics and safety measures. The model estimates the frequency of transfer leaks of different sizes, frequency-quantity distributions and causal breakdowns.

This paper explains the model's methodology and presents preliminary results for standard transfer scenarios. Being traceable to documented analyses of recent leak experience in actual fuel transfer operations, these results are much higher in quality than any previous estimates of transfer leak frequencies. Once validated by industry, they will greatly improve the validity of quantitative risk assessments of fuel transfer operations.

Keywords: Risk assessment, fuel transfer, leak frequencies, arms, hoses.

1. Introduction

The safe transfer of liquids and liquefied gases between transport units and fixed installations is a vital part of the fuel supply infrastructure. Leaks during transfer endanger people working in ports or living nearby. Large or frequent leaks could undermine the public acceptability of the fuel supply, which is particularly important for new low-carbon fuels such as ammonia and hydrogen.

Risk assessments of fuel supply operations need to estimate the likelihood of such leaks. The difficulty and uncertainty of such estimates has been well-known since the first risk assessments of liquefied natural gas (LNG) over 40 years ago (Welker 1976). Several recent studies have shown that these uncertainties are still large and critical for risk assessments of fuel transfer (Gerbec & Aneziris 2020, Spouge 2021).

In the Netherlands, standard leak frequencies have been adopted for such scenarios in the Reference Manual Bevi (RIVM 2021). Its leak frequencies for flexible hoses and articulated arms come from judgements or unknown data sources from the 1960s, which have been copied from study to study ever since (Spouge 2015). The main alternative source was derived by Technica (1990), and is still used by the Health & Safety Executive (2017), although it is now over 30 years old. Other recent guidelines on LNG risk assessments are based on combinations of assumptions and old or unknown datasets from previous studies, typically concealing this fact from the user (e.g. NFPA 2019).

The RIVM therefore commissioned DNV to develop updated leak frequencies for transfer operations taking account of current safety measures. Following a review of possible data sources, the model was based on a detailed analysis of sources with the highest quality ranking. The new model takes account of site-specific operational characteristics and safety measures, and estimates the frequency of transfer leaks of different sizes, frequency-quantity distributions and causal breakdowns. This paper explains the model's methodology and presents preliminary results for standard transfer scenarios.

2. Sources of Leak Frequency Data

2.1. *Review of Sources*

Most existing sources of transfer leak frequencies cannot be traced to any recent collection of leak experience, but this is not because no better sources are available. DNV identified 35 different data sources that could be used to develop updated transfer leak frequencies. This included sources from the following areas:

- Marine, i.e. transfers between ship and shore, including cargo loading/unloading in ports and terminals, and bunkering with marine fuel oil.
- Road/rail, i.e. transfers between road/rail tankers and stationary tanks.
- Aviation, i.e. transfers between refuelling vehicles and aircraft.

Only sources of original leak frequency data (i.e. instances of leaks and estimates of transfer activity) were included. This excluded sources that reproduced earlier data, sources that made expert judgements or assumptions about leak frequencies, and sources that developed transfer frequency models based on the data.

2.2. *Quality Ranking*

To select the best sources, DNV ranked the sources according to their "quality", which in this case means their suitability for updating transfer leak frequencies.

The following quality criteria were used:

- Practicality. Can transfer incidents be readily extracted?
- Relevance. Does the data address fuel transfer operations comparable to those in the Netherlands or other high-income countries?
- Database size. How many transfer leak incidents are included?
- Recency. How recent is the data reporting period?
- Comprehensiveness. Are all leak incidents included, within a defined reporting threshold and period?
- Incident descriptions. Are the causes of all incidents investigated and reported?
- Leak quantities. Are the leak quantities known?
- Activity data. Is the number of transfers known?
- Industry knowledge. Are typical transfer practices (such as the transfer duration and flow rate, and the safeguards in place) known?
- Non-confidentiality. Are incident reports available, and can they be published without confidentiality restrictions?
- Acceptance. Are leak frequencies already in the public-domain and widely used?

Based on a simple scoring system, combining all the criteria, this gave a relative quality score for each source. In some cases, it was possible to combine individual sources to improve their coverage. The best available sources were then used for the model.

2.3. Selected *Sources*

The six selected sources were as follows:

- Marine oil tanker transfer spills world-wide during 1992-2010. This combined several leak sources with activity data from the IHS Fleet Database and the United Nations Conference on Trade and Development (UNCTAD). It covered spills of 1 tonne or more (Spouge 2019).
- Marine LNG tanker transfer spills world-wide during 1964-2015. This combined several leak sources with activity data from the IHS Fleet Database. It covered spills of 100 kg or more.
- Gasoline road tanker transfer spills in the USA during 2000-16. This combined leak data reported by the Pipeline and Hazardous Materials Safety Administration (PHMSA) with activity data from the Bureau of Transportation Statistics (BTS). It covered spills of 15 kg or more.
- LPG road tanker transfer spills in the USA during 2000-16. This combined PHMSA leak data with BTS activity data. It covered spills of 1 kg or more.
- Marine oil bunkering spills in Australia during 1982-2010. This combined data from the Australian Maritime Safety Authority (AMSA) with bunkering activity estimates by DNV. It covered spills of 50 kg or more.
- Marine LNG bunkering spills in Norway during 2000-16. This used data from the

Norwegian Maritime Authority. It covered spills of 1 kg or more.

The data periods were chosen as having the largest possible datasets with high quality and consistent reporting. The reporting thresholds were deduced from the leak size distributions, because either no reporting threshold existed or the data appeared not to follow the official threshold.

3. Model Methodology

3.1. *General Approach*

The aim of the transfer leak frequency model is to estimate leak frequencies for use in risk assessment of transfer operations. The results should be up-to-date and take account of site-specific operational characteristics and safety measures.

The development of the model involved:

- Definition of the scope boundaries for the leak frequencies.
- Definition of the inputs that define the key site-specific operational characteristics and safety measures.
- Selection of failure cases, representing generic leak causes.
- Quantification of failure case frequencies and size distributions.
- Selection of modification factors, which adjust the frequencies and size distributions to represent specific inputs, as well as correcting for trends.
- Estimation of uncertainties in the results.
- Consistency checks of the model against the input datasets.

These stages are described in turn below.

3.2. *Model Scope*

The model scope can be adjusted within limits defined by the coverage of the selected datasets. These include the following system components:

- Transfer equipment, i.e. hoses or arms.
- Equipment on the tanker between its storage tanks and the transfer equipment.
- Road/rail tanker tank shell.
- Tank vents on the tanker, but only for leaks due to overflow or overpressure caused by tanker loading.
- Tank vents on the storage tank, but only for overflows caused by road/rail tanker unloading.

Figure 1 illustrates the scope limits.

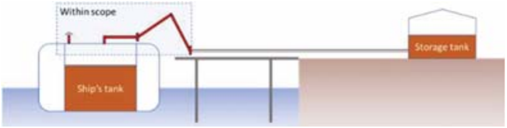

Fig. 1a. Scope Limits of Leak Sources for Marine Cargo Transfer.

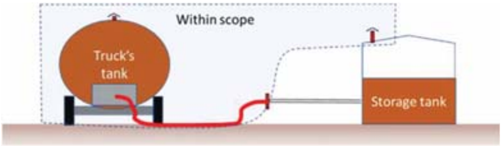

Fig. 1b. Scope Limits of Leak Sources for Road Cargo Transfer.

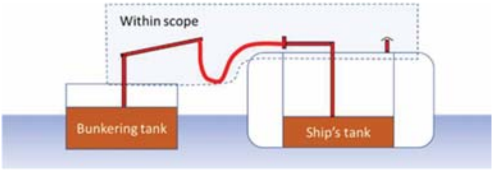

Fig. 1c. Scope Limits of Leak Sources for Marine Bunkering.

3.3. *Model Inputs*

The model allows the user to represent a specific transfer operation by selecting from various inputs (see Table 2 below).

3.4. *Failure Cases*

The model includes a set of failure cases, i.e. generic leak causes with characteristic frequency metrics. These are intended to match the available causal data and allow the model to represent the key features of different transfer types.

The failure cases are as follows:

- Transfer equipment failure, i.e. leak from hose, arm or loading system. For clarity in the model, this is split into hose failure and arm failure.
- Tanker equipment failure, i.e. leak from equipment between the manifold or hose reel and the tanks on the tanker. This includes leaks from pipes, flanges, manifold, or associated valves, gauges, fittings etc.

Pumps are included for road tankers but excluded for marine tankers.

- Tanker tank failure, i.e. leak from shell of road/rail tanker. The corresponding case for marine tankers is outside the scope.
- Connection failure, i.e. leak from the connection of the hose/arm to the tanker or terminal. This includes cases of unwanted emergency release coupling (ERC) activation.
- Valve error, i.e. leak from valves due to human error. This includes incorrect valve alignment, premature opening of valves, or any other operational cause except incorrect closure causing back-pressure.
- Back-pressure, i.e. leak due to over-pressurisation of tank. This includes tank vent failure, incorrect closure of valves causing overpressure, creation of airlocks resulting in backflow and vapour recovery faults.
- Overflow, i.e. leak from tank vent due to excess delivery quantity. This includes delivery into wrong tank, failure to monitor tank level, failure to reduce flow rate, misjudgement in topping off, overpressure etc.
- Disconnection error, e.g. leak due to premature disconnection, failure to contain drained product etc.
- Mooring failure, i.e. leak from transfer equipment caused by marine tanker movement due to mooring error, mooring faults, weather, tide, heeling, waves from passing vessels etc.
- Striking, i.e. leak caused by third-party interference. This includes marine tanker movement due to collision with other ships, and other vehicles running over road tanker hoses.
- Impact, i.e. leak caused by tanker impact on the terminal facilities. For marine tankers, only impacts on floating hoses are included. Impacts on the terminal berth are outside the scope.
- Drive-off, i.e. leak caused by road/rail tanker attempting to leave the transfer point before disconnection, severing the hose.

The user can switch off any unwanted failure cases.

3.5. *Quantification*

The selected datasets are used to quantify the frequencies of each relevant failure case, using the metrics shown in Table 1. The choice of metrics is based on judgement, since no data can demonstrate objectively which metric is most appropriate.

Table 1. Frequency Metrics for Failure Cases.

TRANSFER PHASE	FAILURE CASE	FREQUENCY METRIC
Arrival	Impact	per transfer
Connection	Connection failure	per hose/arm connection
	Valve error	per transfer
Delivery	Hose failure	per hose hour
	Arm failure	per arm hour
	Tanker equipment failure	per hour
	Tanker tank failure	per hour
	Mooring failure	per hour
	Striking	per passing movement
Topping-off	Back-pressure	per transfer
	Tanker tank overflow	per loading
	Delivery tank overflow	per delivery
Disconnection	Disconnection error	per hose/arm connection
Departure	Drive-off	per transfer

This approach ensures that the resulting frequency (when all relevant failure cases are summed) is neither simply proportional to the number of connections nor the transfer duration, but to a realistic combination of the two.

The probability distributions of leak quantity are assumed to depend on the transfer flow rate, and therefore have been converted into probability-duration (PD) distributions for each dataset. Due to lack of data on long duration leaks, the distributions are truncated at arbitrary durations larger than experienced to date. Combining this with the transfer rate and the overall frequency of the failure cases gives a frequency-quantity (FQ) distribution that takes account of the specific flow rate in the transfer operation.

The model also estimates the distribution of the leaks by hole size. Four hole sizes are distinguished:

- Small leaks, with diameter 1% of the hose/arm diameter, or leak area 0.01% of cross-sectional area.
- Large leaks, with diameter 10% of the hose/arm diameter, or leak area 1% of cross-sectional area.
- Full-bore leaks, with diameter equal to the hose/arm diameter.
- Multiple full-bore leaks (if more than one hose/arm is in use), with the cross-sectional area of all hoses/arms in use.

The failure case frequencies are distributed by hole size based on the available leak data.

3.6. *Modification Factors*

The effects of site-specific operational characteristics and safety measures, as well as trends with time, are represented in the model using modification factors (MF).

For adjustments to the failure case frequencies, the MF describes the change in frequency compared to the average for the transfer type:

$$\text{MF} = \frac{\text{Failure case frequency in specific operation}}{\text{Average failure case frequency for the transfer type}}$$

The MFs are derived from data, where available, and judgement otherwise. An MF for any site-specific feature requires leak data and transfer activity to be split into cases with and without it. For example, if 50% of transfers had an emergency release coupling (ERC) and they experienced only 17% of leaks, the MF with ERC would be 0.17/0.5=0.33 while the MF without it would be 0.83/0.5 = 1.7. Alternatively, this could be obtained by a judgement that adding an ERC reduces the leak frequency by a factor of 5.

This allows the frequency in a specific operation to be estimated by multiplying the generic failure case frequencies by the relevant MFs. This is used to represent the effects of most of the user inputs. An exception is emergency shut-down (ESD), which mainly affects the leak duration, and so its MF is applied to the generic PD distribution.

3.7. *Uncertainties*

Due to limitations in the available data, several aspects of the model are uncertain. These could be improved by further data collection or validation through expert judgement from industry. The main areas of uncertainty are:

- Possible under-reporting of small leaks.
- Absence of inputs for geographical region and safety management.
- Use of leak duration and transfer flow rate to characterise the leak severity and the effect of ESD.
- Use of different datasets to estimate failure case frequencies for different tanker types.
- Lack of data on operational characteristics and safety measures in the exposed population.
- Use of LNG tanker data with assumed MFs for other liquefied gas tankers.
- Truncation of FQ distributions.
- Lack of linkage between frequencies and leak quantities.

The model includes indicative uncertainty ranges of approximately a factor of 10 higher or lower. At present, these do not respond to the selected inputs. In principle, as the model inputs deviate from the base data, the uncertainties should increase.

3.8. *Consistency Checks*

At present, the best available data has been used to develop the model. The model has been checked for consistency against the input datasets, but this only provides a basic check that the model correctly matches their results. In fact, because the input datasets combine numerous transfers of different types, while the model addresses specific transfers, the agreement with the input data is only approximate. In future work, it is intended to validate the model against new data that has not been used in model development.

Table 2. Inputs for Transfer Scenarios.

Scenario	1	2	3	4	5	6	7	8
Name	**Crude oil tanker**	**Oil product tanker**	**LNG tanker**	**Gasoline road tanker**	**LPG road tanker**	**Oil bunkering**	**LNG bunkering**	**Ammonia rail tanker**
Transfer type	Cargo loading/ unloading	Cargo loading/ unloading	Cargo loading/ unloading	Cargo loading/ unloading	Cargo loading/ unloading	Bunkering	Bunkering	Cargo loading/ unloading
Transport mode	Marine	Marine	Marine	Road	Road	Marine	Road	Rail
Flow direction	Both directions	Both directions	Both directions	Both directions	Both directions	Delivery	Delivery	Delivery
Fluid type	Crude oil	Other oil	LNG	Light distillate	LNG	Fuel oil	LNG	Crude oil
Tanker type	Crude oil tanker	Oil product tanker	LNG tanker	Liquid road tanker	Liquefied gas road tanker	Bunker tanker	Liquefied gas road tanker	Liquid rail tanker
Transfer equipment	Arm	Hose	Arm	Hose	Hose	Hose	Hose	Arm
Hose/arm type	Single-wall	Rubber	Single-wall	Rubber	Composite	Rubber	Composite	Single-wall
No of hoses/arms	3	1	3	1	1	1	1	1
Flow type	Pumped	Pumped	Pumped	Gravity	Pumped	Pumped	Pumped	Pumped
Transfer frequency (per year)	1	1	1	1	1	1	1	1
Quantity transferred (tonnes)	100,000	5,000	73,000	25	5	2,500	20	100
Transfer duration (hours)	19	8	12	0.5	0.67	10	1	2
Hose /arm diameter (mm)	400	250	400	50	50	100	50	100
Passing movements (per hour)	0.53	1.25	0.83	0.83	0.83	1	0	0
Average flow rate (tonnes per hour)	1,754	625	2,028	50	7.5	250	20	50
Transfer location	Average location	Tidal berth	Tidal berth	Average location	Average location	Average location	Marine vessel	Average location
ESD	Average ESD	Average ESD	Advanced ESD	Average ESD	Average ESD	Average ESD	Average ESD	Average ESD
ERC	Average ERC	Average ERC	ERC	Average ERC	Average ERC	Average ERC	Average ERC	Average ERC
Time period	All data	All data	All data	All data	Late 2010s	All data	Late 2010s	Late 2010s

4. Results

4.1. *Standard Cases*

The following transfer scenarios have been selected to obtain representative standard results cases from the model:

1. Crude oil tanker transfer.
2. Oil products tanker transfer.
3. LNG tanker transfer.
4. Gasoline road tanker transfer.
5. LPG road tanker transfer.
6. Oil bunkering.
7. LNG bunkering from road tanker.
8. Ammonia rail tanker transfer.

Table 2 lists the inputs to the model that are used in each scenario.

4.2. *Results*

Figure 2 illustrates the results from the model for one of the standard transfer scenarios.

CASE 1
Crude oil tanker

OVERALL FREQUENCIES	
Leak frequency (per transfer)	1.3E-04
Transfers (per year)	1
Leak frequency (per year)	1.3E-04

HOLE SIZE BREAKDOWN

Multiple full-bore	**Full-bore**	**Large leak (10% FB dia)**	**Small leak (1% FB dia)**	
693	400	40	4	diameter (mm)
11%	61%	28%	0%	% of frequency
1.4E-05	7.7E-05	3.5E-05	0.0E+00	per transfer
1.4E-05	7.7E-05	3.5E-05	0.0E+00	per year

FAILURE CASE BREAKDOWN	
Arm failure	5%
Tanker equipment failure	31%
Tanker tank failure	0%
Connection failure	20%
Valve error	8%
Back-pressure	0%
Tanker tank overflow	8%
Delivery tank overflow	0%
Disconnection error	2%
Mooring failure	23%
Striking	0%
Impact	2%
Drive-off	0%
Total	100%

Fig. 2. Results for Transfer Scenario 1.

Table 3 summarises the preliminary results from the model, consisting of the overall transfer leak frequency and hole size breakdown for each scenario. The results are described as "preliminary" because they have not yet been validated by industry.

Table 3. Model Results for Transfer Leak Frequencies and Hole Size Distributions.

TRANSFER SCENARIO	LEAK FREQ (per transfer)	MULTIPLE FULL-BORE	FULL-BORE	LARGE LEAK	SMALL LEAK
Crude oil tanker	1.3E-04	11%	61%	28%	0%
Oil product tanker	2.2E-05	0%	69%	31%	0%
LNG tanker	8.2E-05	5%	22%	20%	52%
Gasoline road tanker	3.3E-06	0%	11%	89%	0%
LPG road tanker	2.1E-07	0%	22%	78%	0%
Oil bunkering	1.1E-03	0%	10%	90%	0%
LNG bunkering	2.7E-05	0%	10%	90%	0%
Ammonia rail tanker	7.3E-07	0%	16%	84%	0%

4.3. *Comparison with Reference Manual Bevi*

Because it is based on real data, the current model has a much better foundation than the values for hose and arm failure from Reference Manual Bevi. However, the Bevi values are currently used by industry, so it is important to highlight changes.

Before making the comparison, it is necessary to decide whether to compare the Bevi values with the overall results from the model for the transfer operation (a wide scope), or the individual failure cases (a narrow scope). The two cases are considered in Figures 3 and 4 respectively below.

Figure 3 compares the wide scope results from Table 3 with corresponding results calculated according to Reference Manual Bevi, considering the large leak and full-bore (including multiple full-bore) cases separately.

While some cases show close agreement, others have large differences. Among the leaks, 3 out of 8 cases agree within a factor of 2, while 6 cases agree within the declared factor of 10 uncertainty, but the model for LPG road tankers is a factor of 160 lower than the Bevi value. Among the ruptures, 2 out of 8 cases agree within a factor of 2, while 6 cases agree within the declared factor of 10 uncertainty, but the model for crude oil tankers is a factor of 50 higher than the Bevi value.

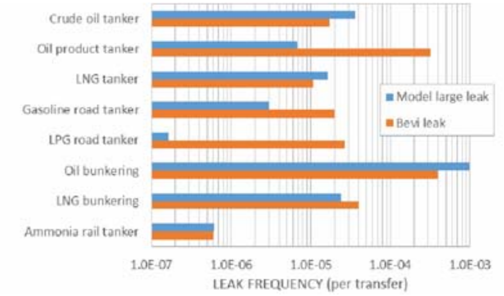

Fig. 3a. Comparison of Wide-Scope Model Results with Reference Manual Bevi (Large Leaks).

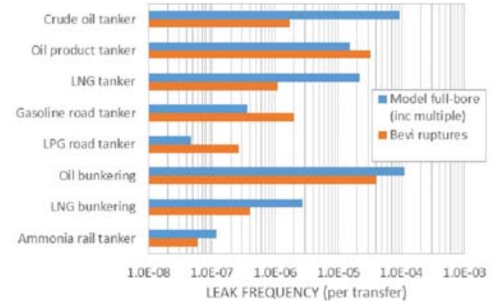

Fig. 3b. Comparison of Wide-Scope Model Results with Reference Manual Bevi (Full-Bore Ruptures).

The largest differences produced by the new model, compared to the Bevi values, reduce small leak frequencies in hose transfers (especially short duration ones), but increase the rupture frequencies in arm transfers (especially long duration ones).

The main reasons for the differences are:

- The Bevi values are expressed per hour and hence the frequency per transfer varies linearly with transfer duration, whereas in the model only some failure cases do this.
- The Bevi values differ between hose and arm but are the same for all transport modes. The model uses different data sources for different transport modes while the difference between hose and arm is less extreme.
- The Bevi values use assumed ratios of leaks to ruptures, whereas the model uses data that may have under-reported leaks.
- The Bevi values only refer to hose and arm failures, whereas the model includes other equipment failures and human errors,

including tank overflows, which dominate some cases.

Figure 4 compares the frequencies for the hose and arm failure case alone from the model with the values from Reference Manual Bevi.

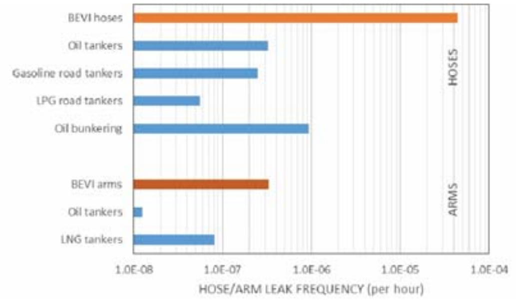

Fig. 4. Comparison of Narrow-Scope Hose/Arm Leak Frequencies with Reference Manual Bevi (including Leaks and Full-bore Ruptures).

It is apparent that the model values for this failure case alone are all lower than the Bevi values. The hose estimates are factor of 50 to 800 lower, while the arm cases are factors of 4 to 26 lower. Hence the differences between their results in Figure 3 arises from the inclusion of other failure cases, not the estimates for hose/arm failure.

5. Conclusions

This study has developed a preliminary leak frequency model, capable of estimating leak frequencies taking account of site-specific operational characteristics and safety measures. The model is described as "preliminary" because it does not yet include review by industry.

The preliminary leak frequency results for standard transfer scenarios mostly agree with the values from Reference Manual Bevi within the model's factor of 10 uncertainty, but in some cases differ from them by factors of up to 160. The largest differences produced by the new model, compared to the Bevi values, reduce small leak frequencies in hose transfers, but increase the rupture frequencies in arm transfers.

The main reasons for the differences are that the model uses data sources, in which the differences between hoses and arms are less significant than failure causes such as connection failures and tanker equipment leaks. The Bevi values depend on the transfer duration, whereas in the model only some failure cases vary in this way while others depend on the number of connections.

In general, the model appears to be realistic and is consistent with available data up to 2016. It therefore appears suitable more for risk assessment of fuel transfer operations than the Bevi values, which are based on judgements or unknown data sources from the 1960s. However, it has not yet been independently validated. The preliminary results should therefore be treated with caution, and checked against new data wherever possible.

Acknowledgement

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