Re-evaluation of the 1995 Hanford Large-Scale Drum Fire Test Results, UCRL-TR-230686

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Purpose and scope of re-evaluation

- **Statistical analysis is performed on the large-scale drum fire test conducted in Hanford in 1995.**
  - **Test results are thoroughly documented in WHC-SD-WM-TRP-246.**
  - **Statistical evaluation of the test data was not performed.**
- **Failure criteria are recommended.**
- **The pallet storage fire test results are emphasized because it is the dominant storage configuration in the DOE complex.**
- **The effect of the flame impingement is verified through simple physical analyses.**

Hanford Large Scale Drum Fire Test

- **WHC-SD-WM-TRP-246, "Solid Waste Drum Array Fire Performance," Rev. 0, Westinghouse Hanford Company, 1995**
  - **144 55-gal drums on pallets were subjected to a 14.5-MW fuel pool fire fire for 5 minutes.**
    - **This is the common storage configuration in a TRU waste storage facility.**
  - **144 55-gal drums on racks were subjected to a 25.9-MW fuel pool fire for 5 minutes.**
  - **Drums were loaded identically with 26 kg of mixed combustibles and 32 kg of noncombustibles.**
  - **Failure data were collected and analyzed.**

Hanford Large Scale Drum Fire Test

- **Seal failure, lid warping, and catastrophic lid ejection were the three failure modes of drums from the test.**
- **There was no discernible failure criterion that distinguished one failure mode from another.**
- **All three failure modes were treated *equally* for the purpose of determining the number of failed drums and failure criteria.**

Hanford Large Scale Drum Fire Test

- **Main observations from the test were:**
  - **Trash expulsion was negligible.**
  - **Flame impingement was identified as the main cause for failure.**
  - **The range of drum temperatures at failure was 600°C to 800°C.**
  - **The critical heat flux required for failure is above 45 kW/m^2.**
  - **Fire propagation from one drum to the next was not observed.**
- **The actual failure rate was less than expected.**
  - **All drums within and directly exposed to the fuel pool fire were expected to fail.**
- **Statistical evaluation of the data was not available.**

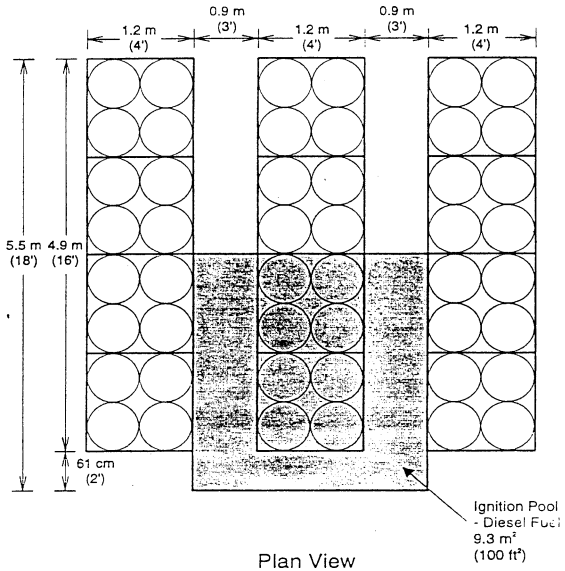
Pallet Storage Fire Test

- A total of 135 liters (36 gal) of diesel was used that was spread over an area of 9.3 m^2.
- In addition, 9.5 gal of gasoline was added to ensure even combustion.
- 144 drums on pallets, four drums on a pallet, were stacked three-level high.
- The magnitude of the fire was 14.5 MW lasting approximately 5 minutes.
- 24 drums were directly inside the fuel pool. Fourteen of the twenty-two (22) drums engulfed in the fuel pool fire failed.

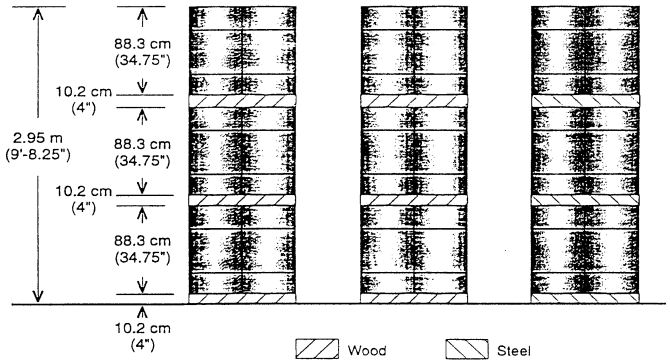
Pallet Storage Fire Test (cont'd)

- **The total number of failed drums, including those with failed seals, was twenty-two (22) as shown in Tables 9 and 11 of WHC-SD-WM-TRP-246. This represents a 15% (22/144) failure rate.**
- **Only three drums, two in the fuel pool fire at the bottom two tiers and one adjacent to the fire at the bottom tier, failed by lid ejection.**
- **Of the remaining nineteen (19) failed drums, seal failure occurred in eleven drums (50% of the total failure).**

Pallet Storage Test



Plan View



Side View

Drums are identified by location: column (x), row (y), and level (z).

Drums in the pallet storage test are identified by "O". In the rack storage, it is "X".

Columns (x) in the pallet test begin with 9 from the left and end at 4 on the right in the plan view.

Rows (y) range from 1 from the bottom to 8 at the top of the plan view. There are three (3) levels (z).

For example, the drum at the bottom left corner at the top level is identified as O913. The drum at the top right corner at the bottom level is O481.

Rack Storage Fire Test

- A total of 265 liters (70 gal) of diesel was spread over an area of 16.6 m^2.
- In addition, 5 gal of gasoline was added to ensure even combustion.
- 144 drums in racks were arranged six levels high.
- The magnitude of the fire was 25.9 MW lasting approximately 5 minutes.

Rack Storage Fire Test (cont'd)

- **The resultant failure rate is 26% (37/144).**
  - **The text in Section 8.2.1 and Section 8.2.2, consistent with that in Figure 58, in WHC-SD-WM-TRP-246 states that a total of 37 drums failed. The number of failures also includes those due to seal failures.**
- **48 drums of the 144 drums were directly in the fuel pool fire, of which 35 drums failed.**
- **Some of the failure data appear to be missing.**
  - **Failure data for only 17 failed drums are reported.**
  - **Instrumentation may not have been available for remaining 20 drums.**

Flame Impingement as main cause for failure, heat flux

- **The average flame emissive power for a fuel pool fire can be calculated using the equation below:**

$$\dot{q}''_{fl} = 140 \times \exp\left\{-0.12 \times D_{eq}\right\} + 20 \times \left(1 - \exp\left\{-0.12 \times D_{eq}\right\}\right)$$

- **The 14.5-MW fire in the pallet storage test fire, the calculated value is 99 kW/m^2.**
- **The calculated average flame emissive power is significantly above the heat flux criterion of "above 45 kW/m^2 ".**

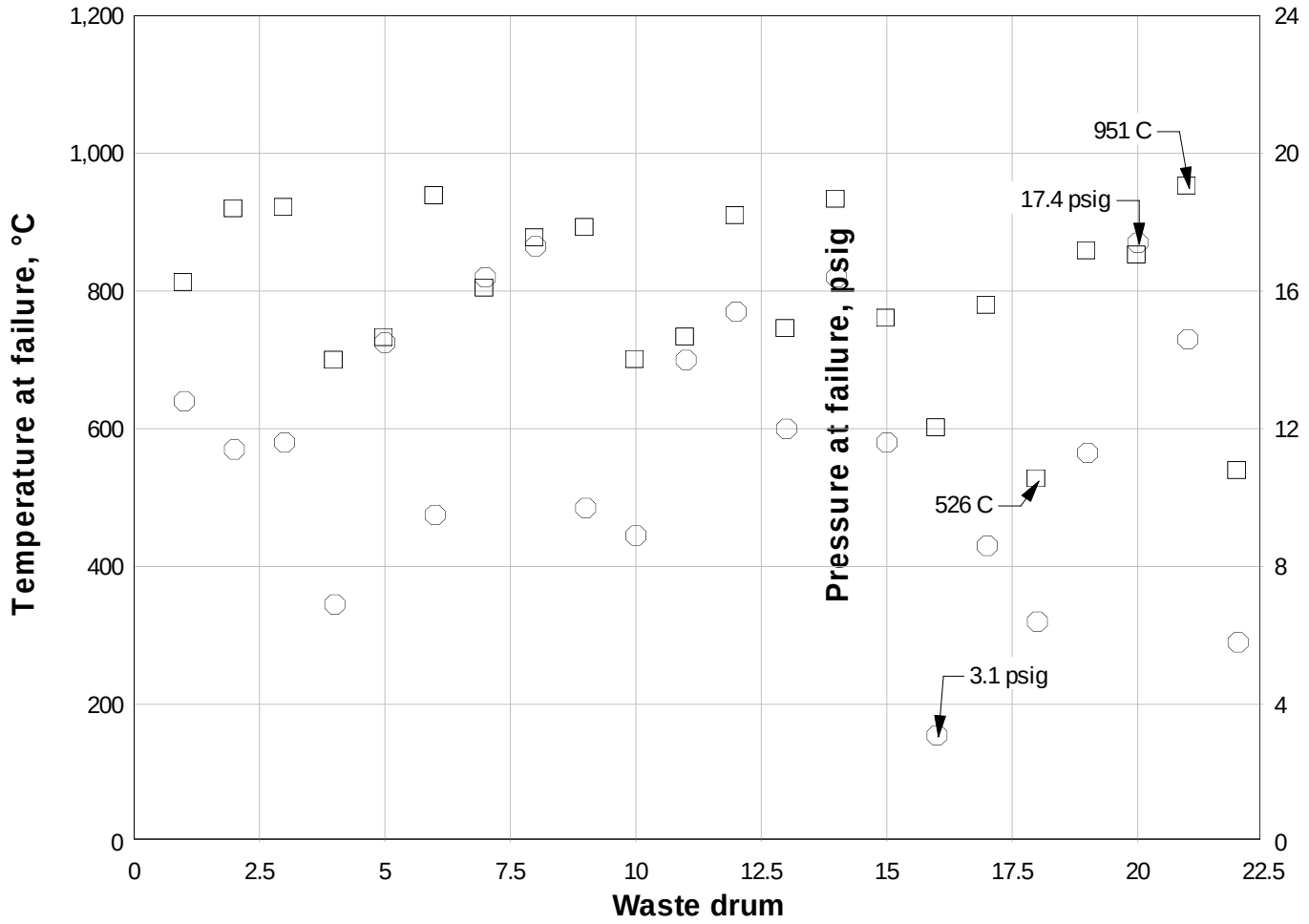
Flame impingement as main cause for failure, temperature

- **The combustion reaction of a stoichiometric octane (main constituent in gasoline) in air is shown below:**

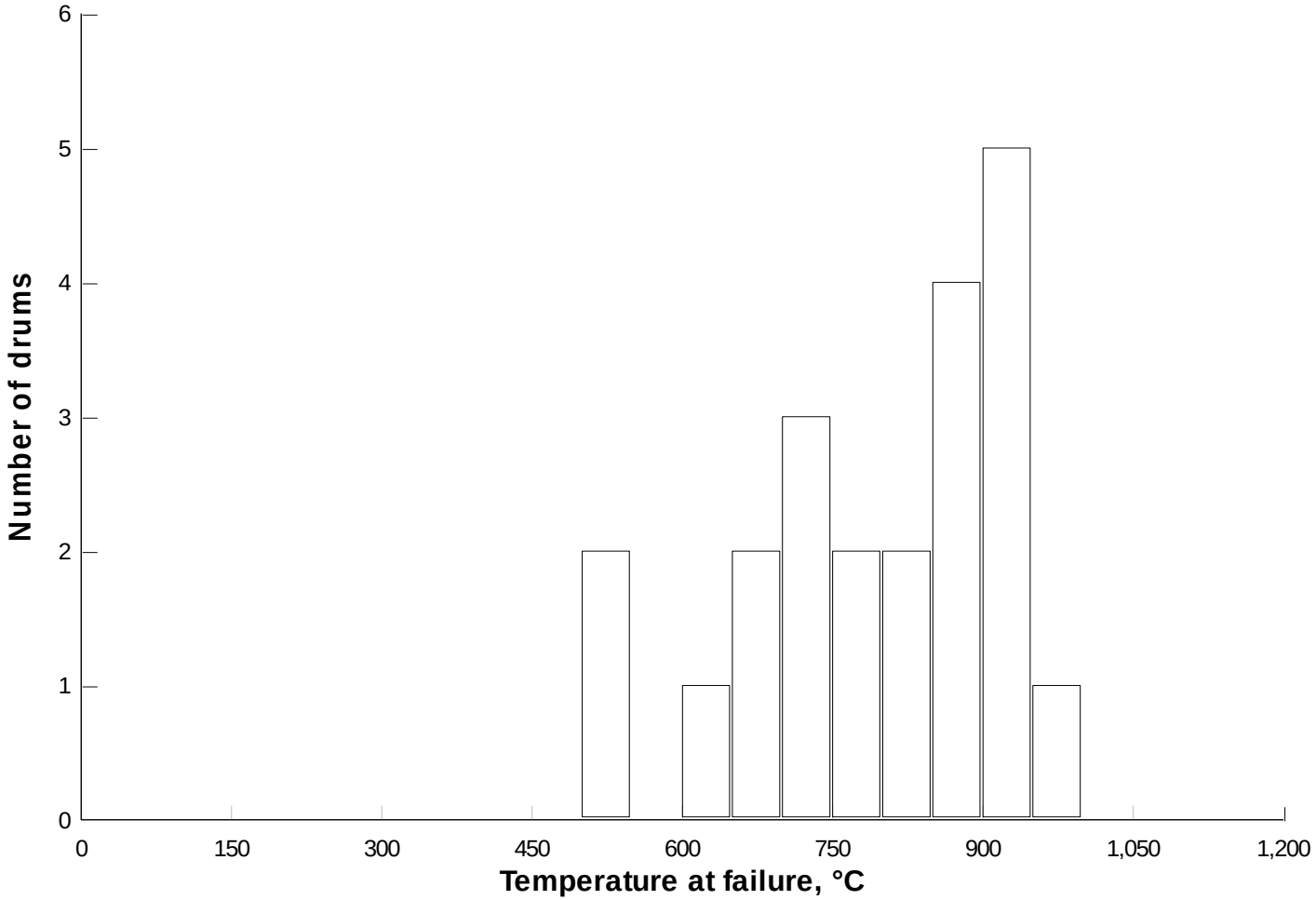
$$C_8H_{18} + 12.5\begin{bmatrix} O_2 \\ 3.76\ N_2 \end{bmatrix} \Rightarrow 8\,CO_2 + 9\,H_2O + 47\ N_2$$

- **The adiabatic flame temperature of the stoichiometric mixture, the theoretical maximum temperature from combustion, is nearly 2,000°C based on a CHEETAH 2.0 analysis.**
- **Even at an equivalence ratio of two (2), a rich mixture, the adiabatic flame temperature exceeds 1,200°C.**

Failure Data from Pallet Storage Fire Test, temperature and pressure



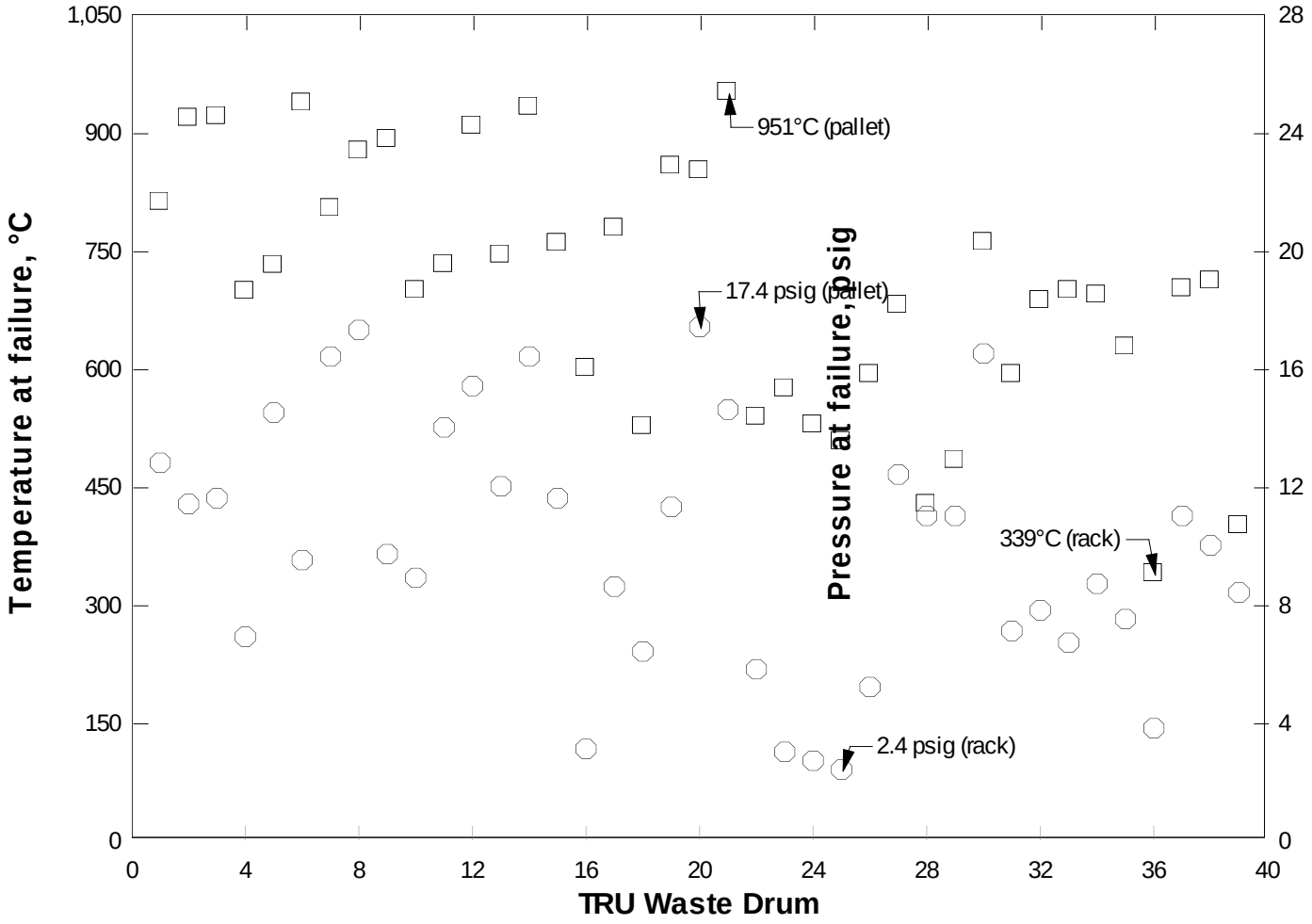
Failure Data from Pallet Storage Fire Test, histogram of temperature



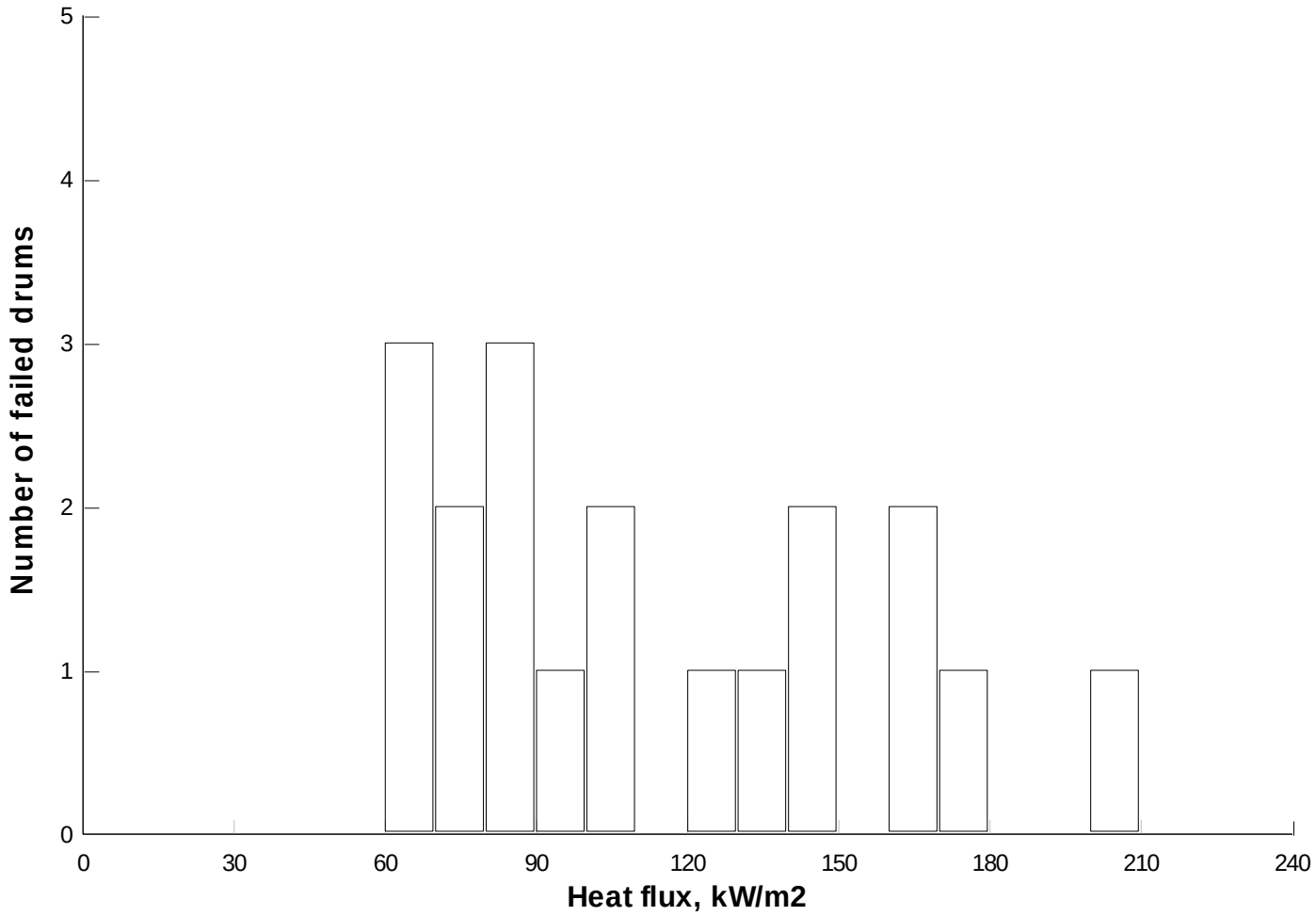
Statistical Considerations

- **The sample size of the available data of the failed drums is small in each test.**
  - **The available data from failed drums are limited to 17 and 22 for the rack storage test and the pallet storage test, respectively.**
  - **The sample size of the heat flux data on failed drums from both tests is even more limited to 19.**
- **It may be prudent to perform a statistical analysis on the combined failure data to assure statistical significance.**
- **It may also be prudent to use statistical results based on a 99% confidence interval because of the small sample size.**

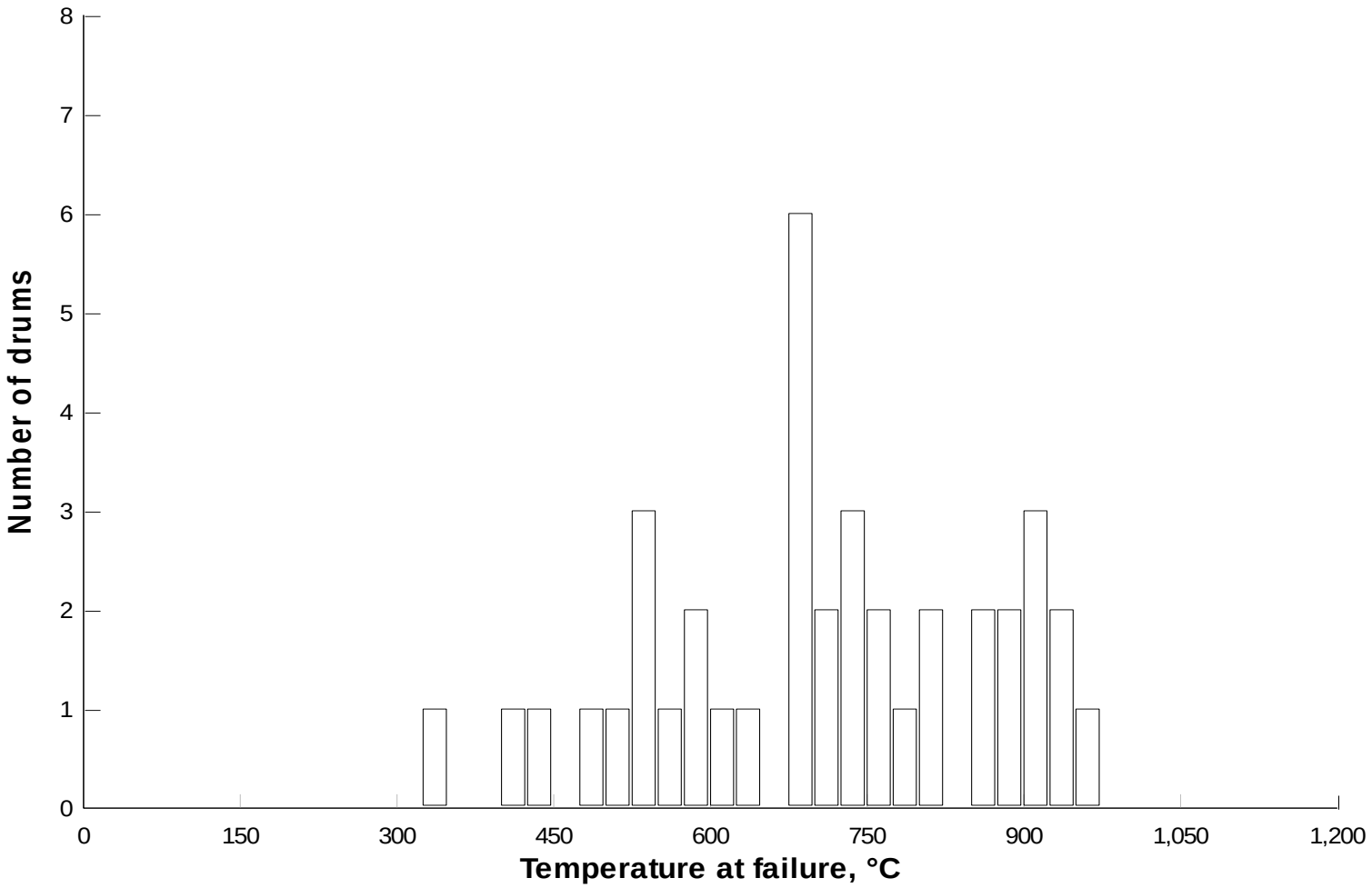
Combined Failure Data, pressure and temperature



Combined Failure Data, histogram of heat flux



Combined Failure Data, histogram of temperature



Statistical Analysis

- **The Student's *t*-distribution is used to derive the failure criteria.**

$$t \equiv \frac{\bar{x} - \mu}{s/\sqrt{N}} \Rightarrow \mu = \bar{x} \pm t \, s/\sqrt{N}$$

where $\bar{x}$ is the sample mean, *s* is the sample standard deviation, and *N* is the sample size.

  - **It was published in 1908 by William Gosset under the pseudonym of "Student".**
  - **The true mean of the failure temperature or heat flux is not known for a large population of failed drums.**
  - **Results depend on the sample size (*N*).**

Statistical Analysis

- **It is assumed in the Student's *t*-distribution that the failure data are normally distributed.**
- **The failure criterion is the lower limit of the mean value, μ, estimated from the Student's *t*-distribution, as follows:**

$$\bar{x} - t \, s/\sqrt{N} \leq \mu$$

- **Failure criteria will be derived with a 99% confidence level (*t* = *t*(0.005) for a two-tailed distribution).**

Temperature at failure

Statistical analysis results of the measured temperature, °C, based on the Student's *t*-distribution

	Sample mean	Standard error of the mean	Sample size	Lower limit of the mean at 95% CL	Lower limit of the mean at 99% CL
Pallet storage	793.6	27.01	22	737.5	717.2
Rack storage	588.2	30.02	17	524.5	500.5
Combined	704.1	25.81	39	651.8	634.1

Heat flux at failure

Statistical analysis results of the measured heat flux at failure, kW/m^2, based on the Student's *t*-distribution

	Sample mean	Standard error of the mean	Sample size	Lower limit of the mean at 95% CL	Lower limit of the mean at 99% CL
Pallet storage	130.5	16.69	8	91.03	72.08
Rack storage	101.8	10.67	11	78.05	68.02
Combined	113.9	9.662	19	93.59	86.08

Results

- **The lowest value from the analysis of the heat flux data, 68 kW/m^2, may be appropriate as a failure criterion in a fire.**
  - **The difference between the sample mean for the heat flux at failure from the rack storage test data and from the pallet storage test data is *not* statistically significant, even at the 99% confidence level.**
  - **The recommended failure criterion will be very conservative in estimating the source term from an exposure fire because of no flame impingement.**
  - **The value is "above 45 kW/m^2 ".**

Results

- **The average failure temperature from the rack storage fire test is 590°C, outside the range of 600°C to 800°C stated in WHC-SD-WM-TRP-246.**
  - **The difference between the sample mean for the temperature at failure from the rack storage test data and from the pallet storage test data is statistically significant at the 95% confidence level.**
  - **One temperature value may not be appropriate as a failure criterion in postulated fires.**

Recommendation, 1/4

- **Trash expulsion is negligible.**
- **Flame impingement is the main cause for failure.**
  - **The calculated flame emissive power of the 14.5-MW fire in the large-scale fire test is 99 kW/m^2.**
  - **The calculated adiabatic flame temperature for octane (main constituent in gasoline) with an equivalence ratio of two (2), i.e., twice as much fuel in the mixture as that in the stoichiometric mixture, is 1,512°K (1,238°C).**
  - **The calculated adiabatic flame temperature and the flame emissive power appear to confirm that flame impingement is the main cause for failure.**

Recommendation, 2/4

- **The critical heat flux required for failure is above 45 kW/m^2.**
  - **The heat flux at failure is not sensitive to the storage configuration and the magnitude of the fire.**
  - **For predicting failures from exposure fires, the currently used threshold radiant heat flux of 45 kW/m^2 appears to be low relative to the test data.**
- **Based on the analysis, a better estimate of the failure criterion is 68 kW/m^2.**

Recommendation, 3/4

- **The reported range of drum temperatures at failure was 600°C to 800°C.**
  - **The test data do not allow a separate analysis to distinguish the effect of the magnitude of the test fire and the effect of the storage configuration.**
  - **It is inferred from the analysis that the temperature at failure is sensitive to the magnitude of the fire and, to a lesser extent, the storage configuration.**
- **For TRU waste drums on *pallets subjected to a severe fire with a magnitude equal to or less than 14.5 MW*, the recommended failure criterion is 700˚C.**
- **When *subjected to a severe fire greater than 14.5 MW*, the recommended failure criterion is 500˚C for all storage configurations.**

Recommendation, 4/4

- **The reported failure rate for drums on pallets was 15%.**
  - **The total number of failed drums on pallets, including those with failed seals, was twenty-two (22) as shown in Tables 9 and 11 in WHC-SD-WM-TRP-246.**
  - **The failure rate includes seal failures, which constitute 50% of the failed drums on pallets. Seal failures of drums would not result in a significant release.**
- **The total failure rate of 20% represents a bounding estimate of the drum failure in the source term calculation.**

Conclusion

- **Summary**
  - **The recommended failure rate of 20% represents a bounding estimate of the drum failure in the source term calculation.**
  - **The recommended failure criterion for the radiant heat flux is 68 kW/m^2.**
  - **For TRU waste drums on *pallets subjected to a severe fire with a magnitude equal to or less than 14.5 MW*, the recommended failure criterion is 700˚C.**
  - **When *subjected to a severe fire greater than 14.5 MW*, the recommended failure criterion is 500˚C for all storage configurations.**

Conclusion

- **The source term estimate for a postulated fire using the recommended failure criteria will be conservative.**
  - **A majority of failures is seal failure that is not expected to contribute significantly to uncontrolled release of materials.**
  - **Expulsion of contents was observed to be insignificant in the test.**
  - **Recommended failure criteria are lower than or consistent with those from the pallet storage test alone.**