An Intercomparison of Water Flow and Gas Flow Laboratories using ISO 5167 Dp Devices

Jos van der Grinten[1], Roy van Hartingsveldt[1], Stefan Knöfel[2], Eberhard Gralla[2] and Johann Kolar[3]

[1] NMi EuroLoop, Petroleumweg 36, 3196 KD Rotterdam-Vondelingenplaat, The Netherlands
[2] Siemens AG, PG ES EN PTEC PP, Erlangen, Germany
[3] Seiko-Flowcontrol Ges.m.b.H, Stockerau, Austria
E-mail corresponding author: jos.vandergrinten@nmi-euroloop.nl

Abstract

This paper describes an intercomparison that has been organized between August 2013 and March 2014, using a ISA 1932 nozzle, a long radius nozzle and a Venturi tube, which were made in stainless steel for the purpose of the project. The devices were calibrated on water, hot water and natural gas by 7 laboratories. The calibration results obtained with water, hot water and natural gas connect well in the overlapping range of Reynolds numbers. For the ISA 1932 nozzle and the long radius nozzle the results of all laboratories agree with at least 95% confidence. The results of the Venturi tube shows significant differences between laboratories at a number of calibration points. The discharge coefficients C_d observed at the A and B tappings generally agree within ±0.1%, with the least differences for the ISA nozzle and the highest for the Venturi tube. One of the remarkable outcomes was the low scatter of C_d for water calibrations of the long radius nozzle and the close agreement to the literature value. The two nozzles produce the most stable results and are suited best for future intercomparisons. The calibration results also demonstrate the possibility to extend the scope of the standard in the Reynolds domain and to lower the standard's uncertainty. This will require more tests with other β ratios.

1. Introduction

In contradiction to the extensive amount of research that has been performed on part 2 of the ISO 5167 [1], describing the performance of orifice plates in a wide range of Reynolds numbers, part 3 [2] and part 4 [3] have a limited scope in applicable Reynolds numbers. These parts of ISO 5167 describe the nozzles, Venturi nozzles, long radius nozzles and Venturi tubes, respectively. Since these devices are commonly used in power plants to establish the mass flow balance, discharge coefficients and accompanied measurement uncertainties have an impact on the Combined Cycle Power plant analysis. Proper research to test and, if possible expand the ISO 5167 would therefore be beneficial for the implication of Nozzles and Venturi tubes.
Between August 2013 and March 2014 an intercomparison was organized using a ISA 1932 nozzle, a long radius nozzle and a Venturi tube. The devices were made by Seiko in stainless steel according to the ISO 5167-3 [2] and ISO 5167-4 standard [3] and are equipped with double pressure tappings. Two sections were made: a Venturi section and a section with interchangeable ISA and long radius nozzle.

Table 1: Calibration conditions during calibration of Dp devices.

Fluid	**Labs**	**t** **[℃]**	**p** **[bara]**	**Re_D** **[-]**
Water	A,B,C.D	20 / 40	-	$7.2{\cdot}10^5$ - $2.5{\cdot}10^6$
Hot water	H	80	-	$2.5{\cdot}10^6$ - $1{\cdot}10^7$
Natural Gas	E,F,G	10 - 20	45 - 50	$3.5{\cdot}10^6$ - $2.4{\cdot}10^7$

Six ISO 17025 accredited laboratories and one ISO 9001 certified lab across Europe performed flow tests on either natural gas, water or hot water on these three delta pressure devices. An overview of the calibration condition and the corresponding Reynolds numbers is shown in Table 1. One lab participated with two fluids. The results are anonymized with respect to the participating laboratories, which are marked by capitals A – H.

The following questions are underlying this intercomparison.

1. Is it possible the extend the scope of the ISO 5167-3,4 standard [2],[3] in the Reynolds domain?
2. Is it possible to reduce the uncertainty presently quoted in the standards for ISA nozzles, long radius nozzles and Venturis?
3. Do laboratories agree with respect to the observed discharge coefficients? And which device would be the most suited for intercomparison exercises?

2. Description of mass flow devices

Figure 1 shows the 12” Venturi Mass Flow Section that was manufactured by Seiko as one piece. For the ISA 1932 Nozzle and the high β ratio Long Radius Nozzle a 12” inlet and a 12” outlet spool was made. The Nozzles are clamped between two ANSI 300#RTJ flanges and can be interchanged. The Venturi is a machined device. The end flanges of all spools are ANSI 600#RF. A flow profiler according to ASME PTC-6 [4] is installed in all Mass Flow Sections upstream of the Dp device. Two sets of pressure tappings A and B are installed at ±45° with respect to the top of the tube.

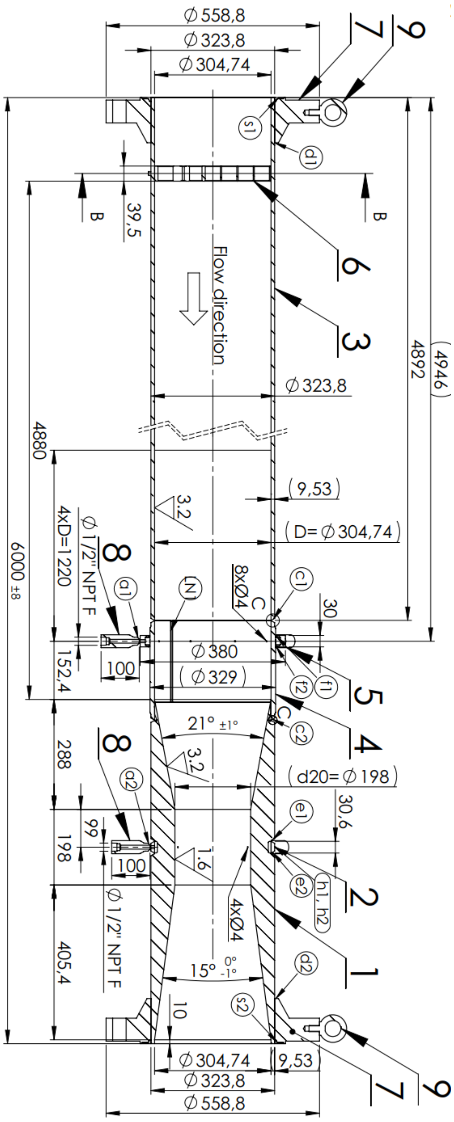

Figure 1: As-build drawing of the Venturi tube. The flow conditioner is marked with 6.

Table 2: Identification and characteristics of all Dp devices.

Device	Pipe diameter D20 [mm]	Device-diameter d20 [mm]	β ratio [-]	Serial No.
ISA 1932 Nozzle	307.225	179.975	0,59	SEI 13-1506
Long Radius Nozzle (High ratio β)	307.345	179.975	0,59	SEI 13-1507
Venturi Tube (Machined)	307.963	197.966	0,64	SEI 13-1505

The dimensional characteristics of all Dp devices are given in Table 2. All inlet pipe diameters are equal within 0.3%. The dimensions of all three Dp devices match the scope of the corresponding standard, which is summarized in Table 3.
Table 3 also shows that the operating scope in terms of Reynolds numbers is limited, especially for the machined Venturi tube. The capabilities of the laboratories clearly exceed the operating scope of the standard. The C_d is the discharge coefficient that is valid if the dimensions of the device are in conformity with the standard. The uncertainty $U(C_d)$ indicates the range around the C_d where calibrated C_d values are assumed to be found.

Table 3: Performance according to the scope of ISO 5167-3,4 (2003).

	ISA 1932 Nozzle	Long radius Nozzle, high β	Venturi Machined
β [-]	0.44 ~ 0.80	0.25 ~ 0.80	0.40 ~ 0.75
d [mm]	50 ~ 500	50 ~ 630	50 ~ 250
$Re_D/10^6$ [-]	0.02 ~ 10	0.01 ~ 10	0.2 ~ 1
C_d [-]	Eq. (3) in [2]	Eq. (8) in [2]	0.995
$U(C_d)$ [-]	$\beta \leq 0.6$: 0.8% $\beta > 0.6$: $(2\beta$-0.4)%	2.0%	1.0%

3. Planning and calibration programme

The laboratories performed calibration at scheduled dates between August 2013 and March 2014. In each laboratory the calibrations could be attended by the organizers and the participants from the other laboratories. Transportation was organized by Seiko Flowcontrol and Siemens processed the results. After the intercomparison exercise a calibration using hot water was added, which is included in this paper.

The objective of the calibration is to determine the C_d of the Dp device in the Reynolds range that was indicated by the laboratory.

$$C_d = \frac{q_m\sqrt{1-\beta^4}}{\frac{1}{4}\pi d^2\ \varepsilon\sqrt{2\rho_1\Delta p}} \tag{1}$$

where

q_m	mass flow rate, determined by the lab	[kg/h]
ρ_1	mass density at the upstream tapping plane	[kg/m³]
d	throat diameter of the Dp device	[mm]
Δp	Pressure difference between the upstream and downstream tappings	[mbar]
β	ratio of d and D	[-]
D	the inlet diameter	[mm]
ε	expansibility factor	[-]

For incompressible liquids like water the expansibility factor $\varepsilon = 1$. For natural gas ε is calculated according Eq. 4 in ISO 5167-3 [2] and Eq. 2 in ISO 5167-4 [3], which are identical. During calibrations with natural gas values for ε are found between 0.9900 and 0.9999.
In the standards C_d is specified as a function of the inlet Reynolds number Re_D. For the Venturi part of the specification outside the scope is made with respect to the throat Reynolds number Re_d, which are defined as

$$Re_d = \frac{\rho v d}{\eta} = \frac{q_m}{\frac{1}{4}\pi d\eta}, \quad Re_D = \frac{\rho v D}{\eta} = \frac{q_m}{\frac{1}{4}\pi D\eta} \tag{2}$$

respectively. Assuming the viscosity will not change between the inlet and the throat the relationship between the throat Reynolds number and the inlet pipe Reynolds number follows from equation (2):

$$Re_D = \beta\ Re_d \tag{3}$$

4. Results

All calibration results were reported by calibration certificates. Except for one all laboratories issued certificates under ISO 17025 accreditation. The other laboratory issued a certificate based on its ISO 9001 certification.

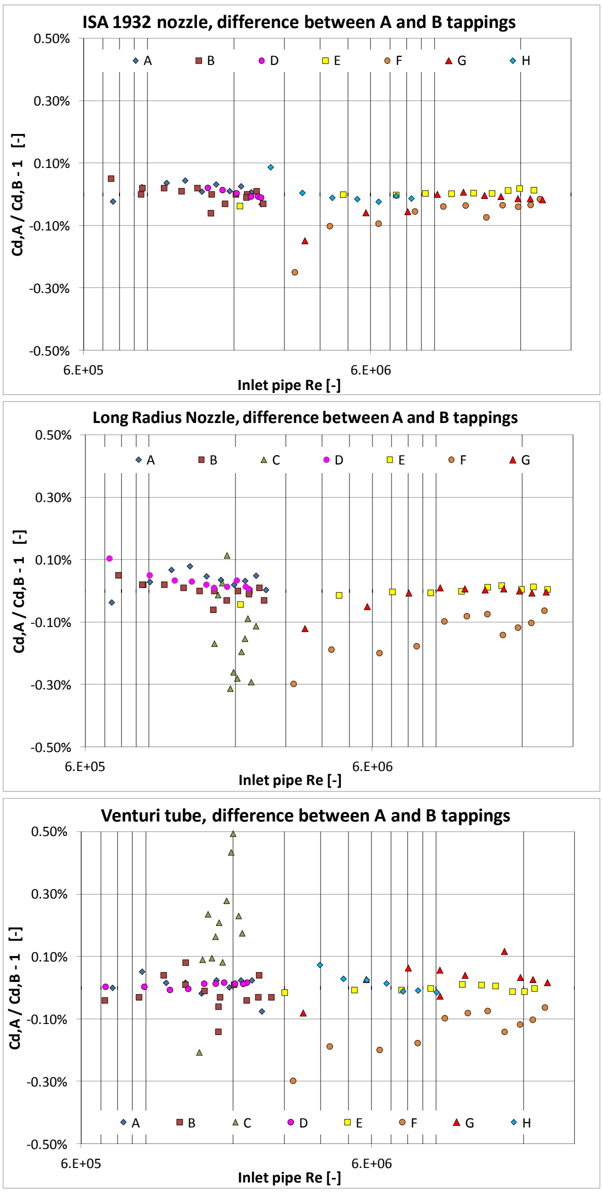

Figure 2: Percentual difference between C_d measured at A and B tappings for an ISA 1932 nozzle (top), the long radius nozzle (middle) and the Venturi tube (bottom) as a function of the inlet Re_D number [-]. The labs are represented by different colour dots. Most results are between ±0.1%. For the ISA nozzle the results of lab C were discarded.

4.1 Differences between A and B tappings

Figure 2 shows the percent difference between the A tappings and B tappings for the ISA nozzle (top) the long radius nozzle (middle) and the Venturi (bottom) versus the *Re* number, which is plotted on a logarithmic scale. Generally, the relative C_d deviation is within a ±0.1% interval. The average differences are (-0.02 ± 0.09)% for the ISA nozzle, (-0.04 ± 0.19)% for the long radius nozzle and (0.03 ± 0.21)% for the Venturi. The best performance is observed at the ISA 1932 nozzle, which shows the best consistency between the A and B tappings. Only two laboratories show higher difference between both tapping pairs. For Venturi tubes differences in C_d between the A and B tappings have been reported in the lower *Re* range of the calibration [5]. A cause for the difference has not been found up till now.

Based on the generally low difference between both tapping pairs it was decided to use the A tapping results for the intercomparison. For the ISA nozzle no results of lab C are available.

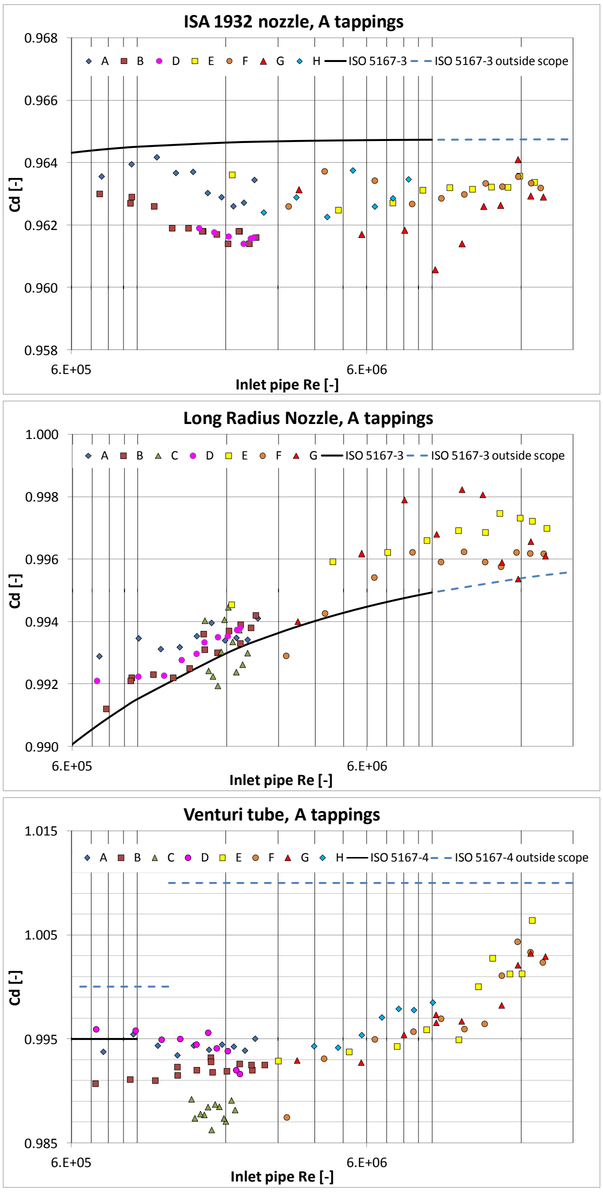

Figure 3: Calibration results for water, hot water and natural gas for the ISA 1932 nozzle (top), the long radius nozzle (middle) and the Venturi tube (bottom), all using the A tappings. The C_d value is depicted versus the inlet Re_D number. The labs are represented by different colour dots. The solid black line is the literature value within the scope of the standard [2] [3], the dashed blue line is the range that is outside the scope.

4.2 Results compared to the ISO 5167 standard

Figure 3 displays the C_d versus the Re_D number plotted on a logarithmic scale for the ISA nozzle (top), the long radius nozzle (middle) and the Venturi tube (bottom), respectively. For the C_d of the ISA and long radius nozzle the scale corresponds to approximately 0.2% per division, for the Venturi the major scale division corresponds approximately 1% and the minor division to approximately 0.2%. For all devices the observations with water, hot water and natural gas connect well. There are no gaps between the observations.

For the ISA 1932 nozzle in Figure 3 all of the observed C_d values are systematically below the literature value. The average deviation from the literature value is (-0.21 ± 0.17)%, the maximum deviation is approximately -0.4%, which is within the standard's uncertainty interval of ±0.8%.
There are no discontinuities in the overlapping range between gas and hot water and the results of the hot water and cold water connect well.

The results of the long radius nozzle in Figure 3 are also well within the interval of ±2% around the literature value. The average deviation between the calibration point and the values predicted by the standard, is (0.09 ± 0.17)% All results are within ±0.3% from the literature value. Most laboratories find results that are above the literature value. Only one water lab makes observations that are below the literature value.

The results of the machined Venturi tube shown in Figure 3 are also well within the uncertainty interval around the literature value. Below $Re = 1 \cdot 10^6$ results coincide within ±0.5% of the literature value (0.995). At higher Re numbers the C_d increases gradually. Except for one date point all results match the scope value of the standard: 0.995 ± 1%. Outside the scope of the standard for machined Venturis, C_d values are defined with respect to the throat Re_d number, which can be converted to the Re_D using equation (3). Table 4 gives an overview for the extended part of the standard [3]. Given the substantial uncertainties of these C_d values all results match these extended reference values.

Table 4: C_d values versus throat Re numbers Re_d for a machined Venturi tube outside the scope of the standard [3]. Re_d values were converted to Re_D using equation (3) and $\beta = 0.64$.

Re_d	Re_D	C_d	Uncertainty [%]
$5 \cdot 10^5 \sim 1 \cdot 10^6$	$3.2 \cdot 10^5 \sim 6.4 \cdot 10^5$	0.995	1
$1 \cdot 10^6 \sim 2 \cdot 10^6$	$6.4 \cdot 10^5 \sim 1.3 \cdot 10^6$	1.000	2
$2 \cdot 10^6 \sim 1 \cdot 10^8$	$1.3 \cdot 10^6 \sim 6.4 \cdot 10^7$	1.010	3

4.3 Intercomparison
For the C_d of the ISA and long radius nozzle the scale in Figure 3 corresponds to approximately 0.2% per division, for the Venturi the major scale division corresponds approximately 1% and the minor division to approximately 0.2%. The C_d uncertainties of the water calibrations range between 0.16% and 0.19%, the uncertainty for the hot water calibration is 0.22% and the uncertainties of C_d obtained with natural gas range between 0.20% for the higher Re and 0.40% for the lower Re numbers.
The objective of an intercomparison is to confirm that laboratories agree. This is the case when the absolute value of the difference of two calibration results is smaller than the expanded uncertainty (k=2) of that difference. In formula:

$$\left|C_{D,1} - C_{D,2}\right| \leq \sqrt{U_1^2 + U_2^2} \qquad (4)$$

where U_1 is the expanded uncertainty of $C_{d,1}$ and U_2 the expanded uncertainty of $C_{d,2}$. The test has a confidence level of at least 95%.
The above means that for water calibrations differences over 0.25% can be considered as significant. Between water and hot water differences over 0.29% are significant. Between natural gas laboratories differences over 0.36% can be significant. When comparing C_d values obtained with hot water and natural gas differences over 0.33% can be significant.
For the ISA nozzle differences between adjacent calibration points are less than 0.25%, which leads to the conclusion that there are no significant differences between the labs. The same observation can be made for the long radius nozzle: all differences over the entire Re range are less than 0.25%.
For the Venturi significant differences occur at $Re_D = 2.2 \cdot 10^7$ between lab E and F and at $Re_D = 1.7 \cdot 10^7$ between lab E and G. Below $Re_D = 1.7 \cdot 10^7$ there are systematic differences between labs A and B and labs B and D. The data of lab C differ significantly from labs A and D.

5. Discussion

5.1 Differences between A and B tappings
The first interesting observation is the difference between the C_d obtained with the A tappings and the C_d with the B tappings. For the ISA nozzle the best consistency between both tappings is observed. The Venturi shows the worst consistency. There are differences between the labs. Some show hardly any difference and others substantial differences. Differences tend to increase at the lower end of the Re range in which the device was calibrated. This behaviour was also observed for as-cast Venturi with a machined convergent section [5]. Stall effects are known to create strong vortices that will disturb the pressure signal. However the cause has not been established yet and more research needs to be done.

5.2 Results compared to the ISO 5167 standard
The curves obtained with water, hot water and natural gas connect well. There are no discontinuities. This means that the selected Dp devices are suited to make a comparison between gas and liquid flows in an overlapping Re range.

For the ISA nozzle the observed C_d results at all labs are systematically lower than predicted by the standard. For the current data set. The dependency of the C_d on the Re number might be approximated by a straight line. The results are well within the uncertainty band given by the standard. Expansion of the scope of the standard to higher Re number seems possible. Also the accuracy may be better than currently published in the standard. At this point it must be noted that only one β ratio was included in the intercomparison whereas the standard includes a β range. Before making adaptations to the standard more evidence must be collected with more parameter variations.

The scatter of data observed at the long radius nozzle equals the 2s value of the ISA nozzle. The water results are remarkably close to the literature value. At higher Reynolds numbers the gas observations show more scatter, however less than at the ISA nozzle. The slope of the curve of the long radius nozzle is steeper than the slope of the ISA nozzle,

The Venturi tube shows the worst stability. The differences of the C_d observed at the A and B tappings is greatest of all devices and also the scatter of the C_d results is bigger than the scatter observed at the other devices. Again the earlier mentioned stall effects may also be responsible for the observed C_d scatter. However the cause of the phenomenon could not be established at this time. In the past some authors made a comparison with gaming technology [6]. Since then quite some work has been undertaken to improve the design of the Venturi [7].
The literature value which is currently only defined in a small range of Reynolds numbers might be extended to $1{\cdot}10^7$. With increasing *Re* numbers the C_d increase at a steeper slope, which was also observed for another type of Venturi [5].

5.3 Intercomparison
For the ISA nozzles and long radius nozzles all results from all laboratories agree with at least 95% confidence. For the Venturi at some Reynolds numbers significant differences between some laboratories are observed, which is caused by the inherent instability of the Venturi tube. The advantage of these Dp packages is that they can be used with any type of fluid as long it is not corrosive ore abrasive. From the devices tested the best choice for an intercomparison would be an ISA nozzle or a long radius nozzle as with these device the least scatter of C_d in the *Re* range is found: 2s = 0.17%. The ISA nozzle has the advantage that the observed difference between A and B tappings is the lowest of devices tested.
The Dp devices used in the current intercomparison can be used for any type of fluid as long it is not corrosive. The packages will be available for future testing.

6. Conclusion and recommendations

From the previous intercomparison measurements and the above analysis the following conclusions can be drawn.

- In the current intercomparison the C_d values connect very well in the overlapping Reynolds range between water, hot water and natural gas. This shows that for the current devices with a specific β ratio the C_d is only depending on the Reynolds number.
- The ISA 1932 nozzle has the lowest difference between C_d observed at the A and B tappings (-0.02 ± 0.09)%. The ISA nozzle has a low dependency on the *Re* number. The average deviation with respect to the standard's C_d is (-0.21 ± 0.17)%. For the current set of observations the literature values may be approximated by a straight line.
- The long radius nozzle shows a scatter equal to the ISA nozzle. The average difference between the standard's C_d and the observations is (0.09 ± 0.17)%. The water calibrations are remarkably close to the literature values.
- For the ISA and long radius nozzles the results obtained by different laboratories agree with at least 95% confidence. For the Venturi tube there are significant differences between C_d observations in the lower Reynolds range.
- The Venturi tube shows the worst stability. The differences of the C_d observed at the A and B tappings is greatest of all devices and also the scatter of the C_d results is bigger than the scatter observed at the other devices.
  The literature value which is currently only defined in a small range of Reynolds numbers might be extended to $1{\cdot}10^7$. With increasing *Re* numbers the C_d increase at a steeper slope, which was also observed for another type of Venturi [5].

The results show that for the current data set lower uncertainties and extension of the scope of the ISO 5167 standard is possible. Adaptation of the standard in this respect requires more devices tested with more β ratios. It is the intention of the authors to make the data available to the ISO committee that is responsible for the ISO 5167 standards. For now the best method for achieving a low measurement uncertainty is to calibrate the device in the appropriate range of Reynolds numbers.

References

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