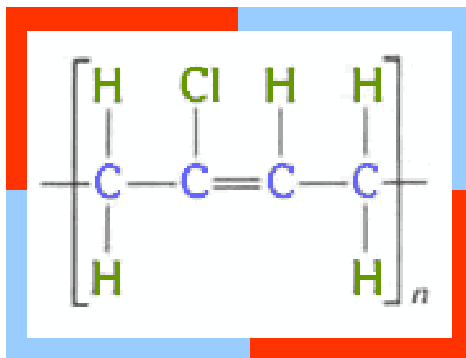


ALERT—High Viscosity Two-Phase Flow Through Relief Valves and Pipes: is anyone doing this right?

ioMosaic Corporation

Background

High viscosity two-phase flow occurs in many industrial scale reactors handling polymer systems. For example, a runaway reaction in a monomer tank can lead to high viscosity two-phase flow. Following such a runaway reaction, polymerization and decomposition products are produced in the reactor and vented through the reactor's emergency relief system.



Many polymerization reactors are equipped with relief devices with discharge lines that are 50 to 100 feet long and in some cases longer. Discharge lines are typically connected to a vent containment header and/or a flare header. A large majority of relief device installations that exist today were designed using best industry practices such as API-520. Several publications have appeared in recent literature indicating that 30 to 40 % of the relief devices that are in existence violate industry guidelines for inlet pressure drop and backpressure. These studies followed the OSHA PSM rule, which requires that the relief device design basis be documented and verified.

What is alarming is that these published numbers refer to relief devices that were sized for all-liquid or all-vapor flow for low viscosity systems. The design of a relief valve for a two-phase discharge introduces more complications. One now has to deal with fluid systems that have the density of a liquid and the compressibility of a gas. Moreover, the fluid can flash as it depressures, thereby limiting the flow capacity of the relief system. Several attempts have been made to bring best industry practices to a point where simple techniques can be used by operating plants to produce a best estimate of a safe design.

We will not dwell on the fact that a good relief design starts with a good design basis along with adequate reaction and physical property data.

It is somewhat ironic that many operating companies today do not have adequate in-house experienced resources for pressure relief design.

We often find that ERS systems (frequently a last line of defense against runaway reactions) that protect the source of all product revenue for a plant are not adequately sized. There have been several incidents reported where the pressure relief system was identified as being inadequate and a contributing cause to loss of life, loss of containment and the associated monetary damage resulting from property loss, business loss, and of security of supply issues.

We will focus in this short white paper on issues pertaining to high viscosity two-phase flow through relief valves.

“30 to 40 % of the relief devices that are in existence violate industry guidelines for inlet pressure drop and backpressure.”



How is it done today and why existing reactors handling high-viscosity two-phase flow are at risk and should be checked by qualified designers with adequate tools?

There are currently no broadly-accepted methods on how to design a relief system for high viscosity two-phase flow. The DIERS Users Group has recently sponsored three research projects focused on producing a consensus-based best practice on how to design such systems. SuperChems for DIERS was released by the AIChE/DIERS Users Group and incorporates such consensus-based techniques based on the results of DIERS research and many years of usage and validation by several operating companies worldwide.

A few problems that even the novice designer will quickly identify:

1. How does one calculate a two-phase viscosity to use for the estimation of two-phase pressure drop in the inlet line and the outlet line?
2. Is there a two-phase flow Reynolds's number? How do I compute it?
3. I know that the choke point for a two-phase mixture is influenced by vapor quality and viscosity. How do I estimate the quality and associated pressure drop at the right location?
4. Does a high-viscosity two-phase mixture separate in the relief valve or in the discharge pipe?
5. How sensitive is the final design to small changes in inlet vapor quality?

Item 1 is at the heart of the problem with two-phase high viscosity flow. There have been several publications over the past thirty years that suggest that a "volume averaged" two-phase viscosity should be used. Variations on this theme were also published assigning different weighting factors to the vapor or liquid portion of the flow.

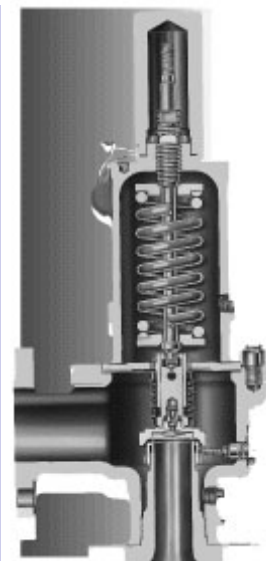
Various techniques published by highly respected engineers and scientists can produce pressure drop contributions for high viscosity two-phase flows in short pipes that differ by 25 to 50 percent.

Recent DIERS Users Group sponsored research is getting closer to a solution. We know based on the results of these studies that flow through safety relief valves is best represented by a homogenous volume-averaged two-phase viscosity. Clearly the valve geometry comes into play here and different manufacturers have different style valves. For example, a valve with a constant diameter bore that is four inches or longer, should be the valve of choice if you must use one for high viscosity two-phase flow. Flow in a short nozzle of less than four inches is best represented by non-equilibrium flow.

The discharge pipe on the other hand is another story. A discharge pipe with a length exceeding 35 L/D will result in separated flow and vapor-liquid slip will become important as the liquid viscosity increases.

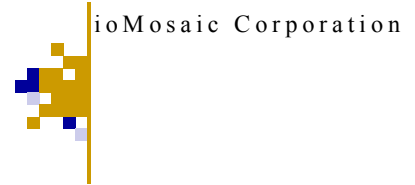
Today's design techniques use the same homogenous volume based two-phase mixture viscosity to estimate pressure drop in the discharge pipe. Most discharge pipes sized using a homogenous volume averaged two-phase viscosity will be undersized. This can lead to valve chattering, possible valve failure, and/or inadequate relief.

SuperChems for DIERS contains two consensus-based techniques that are used for effective design of high-viscosity two-phase flow systems. The relief valve is represented using a volume based two-phase viscosity and the discharge piping is represented using a separated flow model. Design issues associated with high-pressure relief, non-ideal systems, and super-critical systems are common in many processing plants. SuperChems for DIERS represents a unified approach for dealing with all these systems accurately, quickly, and in a user-friendly manner.



"a valve with a constant diameter bore that is four inches or longer, should be the valve of choice if you must use one for high viscosity two-phase flow."

Recent DIERS Benchmarks show that many qualified design engineers often do not produce correct benchmark results for simple design problems with fluids like water on the first try.



Key findings from DIERS Research on high-viscosity two-phase flow

A key finding of the DIERS research program on high viscosity two-phase flow is that a high viscosity two-phase discharge will separate in the discharge line. This is important because slip flow will lead to higher-pressure drop in the discharge line. Preliminary findings suggest that short discharge lines can be undersized by one to two pipe sizes if the pressure drops were estimated with no slip. This can lead to valve chatter and inadequate venting capacities.

The same logic discussed above applies to the inlet line if the inlet quality is greater than zero. The allowable inlet pressure drop is restricted by to 3 % of set. The introduction of slip in the inlet line for non-viscous systems will result in higher-pressure drops and larger inlet line size requirements. Higher viscosity systems will exhibit more slip, and as a result higher pressure drops.

Another key finding is that high-viscosity two-phase flow through relief valves is best represented using a homogeneous equilibrium (no slip) flow and viscosity model. A two-phase mixture exiting the throat of a relief valve strikes the disc surface and changes direction by 90 degrees. At the disc surface, the fluid velocity must be zero. In effect, the flow is being arrested by the disc and is established again as the fluid leaves the valve nozzle and enters the body bowl.

High viscosity two-phase flow velocities are less than two-phase flow with low viscosity. This leads to longer residence times in the valve throat and as a result, homogeneous equilibrium two-phase flow is likely to be established in less than four inches.

Finally, a homogeneous-equilibrium flow model through a relief valve matches low viscosity experimental data as well as the limited data collected on high-viscosity flow.

Safety Valve Representation

Recent DIERS sponsored research on high viscosity two-phase flow suggests that a safety relief valve can be represented using a simple pipe representation of the nozzle. This technique does not require knowledge of a viscosity correction and relies on wall shear to produce the viscosity effects on pressure drop and flow reduction.

Clearly, a simple pipe representation will miss second order effects dealing with more complex valve geometries and entrance effects. SuperChems has two methods of representing a valve: an ideal nozzle method and a pipe method.

Pipe flow solutions in SuperChems are produced by solving differential representations of the mass, momentum, energy, and physical equilibrium relations. In addition to the accelerational, frictional, and gravitational components to pressure drop, SuperChems defines an additional velocity head contribution for a valve to account for the entrance, geometry, and laminar flow development effects:

$$k_c = \left[\frac{1}{k_{lift,inlet}^2} \right] \left[\frac{1}{k_{lift,back}^2} \right] \left[k_{ent,turb} + 1 + k_{lam} \right]$$

The lift components of the velocity head correction to the pipe representation deal with valve lift as a function of overpressure and backpressure. Lift characteristics are available from valve manufacturers or one can use data published by API if manufacturer

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data is not available for a specific model.

The turbulent entrance component, $k_{ent,turb}$ can be estimated from the manufacturer's reported discharge coefficient or preferably established by requiring the pipe representation of the valve to flow the reported capacity of the valve for air or steam. Often, using the reported discharge coefficient works well:

$$k_{ent,turb} = \left(\frac{1}{C_d^2} - 1 \right) (1 - \beta^4)$$

The laminar velocity head, k_{lam} contribution is a strong function of the Reynolds's number and will also depend on the valve geometry to some extent as the flow profile develops. We will show that this contribution is well represented by the Darby-Molavi viscosity correction factor, k_{DM} for both all liquid flow and two-phase flow. This contribution is most important for high viscosity liquids and for short pipes. The value of k_{lam} tends towards zero at high Reynolds' numbers (>3100) and will tend to infinity as the Reynolds number approaches zero.

The published Darby-Molavi viscosity correction is a "discharge coefficient" like correction and needs to be converted to a velocity head loss. It can easily be shown that k_{DM} will collapse to the following k_{lam} velocity head loss form:

$$k_{lam} = \frac{\xi}{Re} + \psi$$

Where,

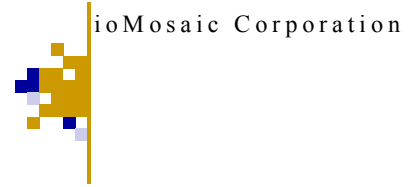
$$\xi = \frac{950(1 - \beta^4)(1 - \beta)^{1.4}}{0.95\beta^{0.1}}$$

and,

$$\psi = \frac{0.9(1 - \beta^4)}{0.95\beta^{0.1}} - (1 - \beta^4)$$

For varying β values of ranging from 0.1 to 0.9, the value of ψ is negligible.

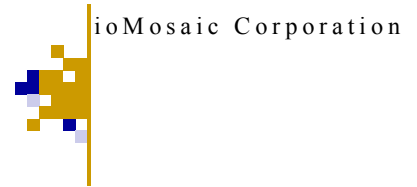
β	ξ	ψ
0.1	1086	0.192
0.2	858	0.112
0.3	679	0.067
0.4	522	0.037
0.5	380	0.014
0.6	254	0
0.7	146	0
0.8	63	0
0.9	14	0



"If you are designing high-viscosity two-phase relief systems, you should qualify you design methods against these simple benchmarks."

"Most discharge pipes sized using a homogenous volume averaged two-phase viscosity will be undersized. This can lead to valve chattering, possible valve failure, and/or inadequate relief."

Interestingly, Grolmes arrived independently at a velocity head correction form that is very similar to the form used by SuperChems based on the Darby-Molavi viscosity correction.



$$k_{c,Grolmes} = k_{ent,turb} + 1 + \frac{0.576}{Re}$$

and

$$k_{c,SuperChems} = k_{ent,turb} + 1 + \frac{\xi}{Re}$$

when the valve is fully open. We proceed to show that an ideal nozzle representation with a viscosity correction coefficient and the pipe representation will produce essentially the same answers and reproduce effectively the same viscosity correction.

DIERS Benchmarks

The following benchmarks are offered in this paper to help operating companies determine if their current design methods will work for high-viscosity two-phase flow. The system is selected to be simple and with a fixed viscosity. We also illustrate the impact of flow quality on relief capacity and discharge pipe backpressure.

If you are designing high-viscosity two-phase relief systems, you should qualify your design methods against these simple benchmarks. You may be surprised with the outcome!

Benchmark 1: All liquid viscous flow

We use a 4P6 safety relief valve with a flow area of 6.38 in², a discharge coefficient of 0.71, and a set pressure of 52.5 psig. The fluid is water at 40 C. Viscosity of the water will be varied from 1 cp to 100,000 cp. The water flowing pressure is 72.6 psia and the backpressure is 14.7 psia. The pipe representation of the valve is a 6-inch line with an inside diameter of 2.85 in and a pipe surface roughness of 0.0018 in.

An ideal nozzle flowing low viscosity water will produce a flow rate of 1,016,485 lbs/hr. The following table compares the flow capacity and flow reduction estimates relative to the 1,016,485 lbs/hr rate. Data is reported for the pipe solution and a simple nozzle estimate using the discharge coefficient and the Darby-Molavi viscosity correction. Both solutions essentially predict the same flow rates and the same viscosity correction factor over a wide range of viscosities.

We note that the laminar velocity head contributions become negligible at Reynolds's numbers larger than 1,500.

	Pipe Solution					Nozzle Solution		
Liquid Viscosity μ (cp)	Flow Rate (lbs/hr)	Flow Reduction	Pipe Inferred Kv	Reynolds's Number	k_{lam}	Lbs/hr	Darby-Molavi Kv	Reynolds's Number
1	690,974	0.68	1.00	2,200,000	0.00	722,100	1.00	2,800,000
10	690,075	0.68	1.00	152,922	0.00	721,726	1.00	190,000
100	686,315	0.68	0.99	15,208	0.00	718,385	1.00	18,900
250	681,749	0.67	0.99	6,043	0.01	712,921	1.00	7,500
500	678,098	0.67	0.98	3,005	0.03	703,781	0.99	3,700
750	675,066	0.66	0.98	1,995	0.05	694,761	0.97	2,440
1,000	665,057	0.65	0.96	1,474	0.08	685,861	0.96	1,800
5,000	538,953	0.53	0.78	239	0.56	559,439	0.79	294
10,000	420,935	0.41	0.61	93	1.47	439,909	0.62	116
100,000	65,210	0.06	0.09	1	95.67	69,297	0.10	2



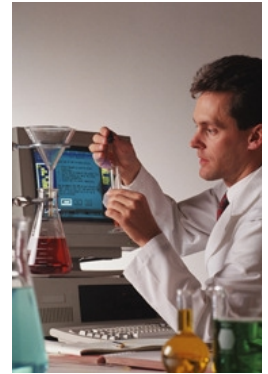
“high-viscosity two-phase flow through relief valves is best represented using a homogeneous equilibrium (no slip) flow and viscosity model.”

Benchmark 2: Two-Phase viscous flow and all gas flow

This is the same safety relief valve as the one used in Benchmark 1. The discharge coefficient used is 0.91 instead of 0.71 and the water liquid viscosity is held constant at 5,000 cp. All else remains the same.

The following table summarizes flow estimates for an ideal theoretical nozzle with no losses. This is the maximum possible flow through the valve without any losses.

Inlet Quality	Flow Rate (lbs/hr)	Choke Pressure (psia)	Choke Temperature (C)	Choke Quality	Choke Reynolds's Number
0.0001	123,957	65.75	148.26	0.007	197
0.001	121,380	65.62	148.19	0.008	213
0.01	104,673	58.49	143.99	0.025	525
0.1	62,454	48.74	137.52	0.122	1,883
0.5	32,962	43.44	133.55	0.502	7,947
0.8	26,773	42.74	132.99	0.782	23,243
0.95	24,771	42.61	132.88	0.922	70,297
0.98	24,426	42.59	132.87	0.950	110,413
0.9999	24,223	42.57	132.85	0.967	266,928



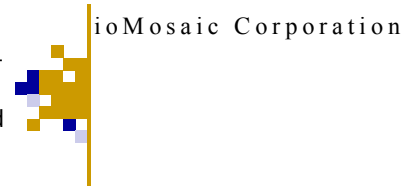
The next table summarizes flow estimates for a theoretical nozzle with losses represented by a discharge coefficient correction and a viscosity correction. These flow estimates are what would be used for actual design if this method is used. The API-520 Kv correction is often used in lieu of the Darby-Molavi form.

Inlet Quality	Flow Rate (lbs/hr)	Choke Pressure (psia)	Choke Temperature (C)	Choke Quality	Choke Reynolds's Number	Choke Viscosity (cp)	Choke Kv
0.0001	83,873	56.38	142.66	0.018	348	560.483	0.813
0.001	84,065	56.51	142.74	0.018	360	541.928	0.818
0.01	81,579	55.51	151.85	0.028	530	357.504	0.867
0.1	54,792	46.97	136.23	0.124	1,911	66.608	0.963
0.5	29,972	43.24	133.38	0.502	7,974	8.731	0.998
0.8	24,363	42.74	132.99	0.782	23,243	2.434	1.000
0.95	22,542	42.61	132.88	0.922	70,297	0.744	1.000
0.98	22,228	42.59	132.87	0.950	110,413	0.467	1.000
0.9999	22,043	42.57	132.85	0.967	266,928	0.309	1.000

The final table for this benchmark summarizes flow estimates from a piping representation of the relief valve.

Inlet Quality	Flow Rate (lbs/hr)	Choke Pressure (psia)	Choke Temperature (C)	Choke Quality	Flow Reduction Factor	Inferred Kv	Inferred Kv / Darby-Molavi Kv
0.0001	83,259	47.20	136.40	0.029	0.67	0.74	0.915
0.001	82,521	46.86	136.14	0.031	0.68	0.75	0.921
0.01	75,674	44.68	134.50	0.042	0.72	0.80	0.920
0.1	48,019	37.42	128.52	0.137	0.77	0.84	0.876
0.5	27,477	35.95	127.20	0.515	0.83	0.92	0.917
0.8	23,050	36.07	127.31	0.796	0.86	0.95	0.953
0.95	21,456	36.80	127.97	0.937	0.87	0.96	0.962
0.98	21,161	36.80	127.97	0.966	0.87	0.96	0.963
0.9999	20,984	36.80	127.97	0.981	0.87	0.96	0.963

The piping solution answers are within a few percent of the corrected ideal nozzle estimates. The flow reduction factor is the pipe flow estimate divided by the ideal nozzle estimates with no loss corrections. This flow reduction factor would be equal to the product of the viscosity correction and the discharge coefficient. The inferred Kv value is obtained by dividing the flow reduction factor by the discharge coefficient.



Benchmark 3: Pressure Drop in Inlet and Discharge Piping For Viscous Two-Phase Flow

A key finding of the DIERS research program is that a high viscosity two-phase flow will separate in the discharge line. This is important because slip flow will lead to higher-pressure drop in the discharge line. Preliminary findings suggest that a short discharge line can be undersized by one or two pipe sizes if the pressure drops were estimated with no slip.

We add a discharge line to benchmark 2 and estimate the required discharge line diameter in order to reach a 30 % backpressure. The discharge line is composed of a horizontal segment (1 ft long), one 90-degree elbow ($k = 800/NRe + 0.3$), and a vertical segment (7 ft long). The liquid viscosity is 5000 cp at 151.8 C and 14305 cp at 100 C.

The following table shows the impact of slip on pressure drop in the discharge line for an inlet quality of 0.0001.

Slip Model	Slip Ratio at Discharge Line Inlet	Slip Ratio at Discharge Line Outlet	Discharge Line OD (in)	% Backpressure	Flow Rate (lbs/hr)
Homogeneous	1	1	6	33.52	83,909
Moody	8.2	11.4	6	50.50	83,672
Moody	9.1	11.4	8	26.67	83,909
Fauske	24.9	40.07	8	42.54	83,909
Fauske	27.97	40.08	10	28.32	83,909

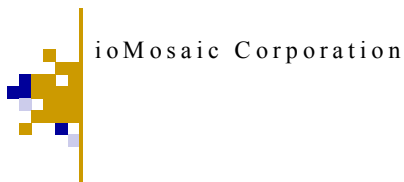
The results show that the discharge line diameter would be six inches using no slip, eight inches using Moody slip, and ten inches using Fauske slip. These results are not meant to produce a heuristic of adding two line sizes to the discharge line when designing using a no slip model; rather they are intended to illustrate the importance of slip on required discharge diameter. The viscosity values and physical properties used here may be different for other polymers. The total discharge line length used here is eight ft. Actual installations typically have discharge lines of 50 or 100 ft connecting into headers or other equipment. For those situations and with high viscosity flows, the use of rupture disks should be considered.

Recommendations

The following design recommendations apply to both low and high viscosity two-phase flow systems:

1. Use a homogeneous equilibrium model (no slip) to represent a safety relief valve that has a constant diameter bore of four inches or greater; otherwise, use a homogeneous non-equilibrium model.
2. Use a slip flow model to estimate pressure drop and backpressure for the inlet and discharge lines.
3. A piping representation of a relief valve is preferred over an ideal nozzle representation. Estimate the turbulent entrance correction using published manufacturer air or steam flow where possible. If flow data is not available, estimate the entrance correction using the published discharge coefficient. Using this approach eliminates the guess work from having to establish a discharge coefficient for different types of flows such as frozen, hybrid, flashing, etc.

“The introduction of slip in the inlet line for non-viscous systems will result in higher-pressure drops and larger inlet line size requirements.”



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References:

1. R. Darby, "Viscous Two-phase Flow in Safety Relief Valves. Phase I. Present Status and Recommended Design Procedures, DIERS Users Group Final Report, November 20, 1997.
2. M. Grolmes, "Progress Report on High-Viscosity Two-Phase Flow Modeling", DIERS Users Group, April 1997.
3. M. Grolmes, "High-Viscosity Two-Phase Flow Modeling", DIERS Users Group Draft Final Report, June 2002.

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Dr. Georges Melhem is managing general partner of ioMosaic Corporation. Prior to ioMosaic Corporation, Dr. Melhem was president of Pyxsys Corporation; a technology subsidiary of Arthur D. Little Inc. Prior to Pyxsys and during his twelve years tenure at Arthur D. Little, Dr. Melhem was a vice president and managing director of Arthur D. Little's Global Safety and Risk Management Practice and its Process Safety and Reaction Engineering Laboratory.

Dr. Melhem is an internationally known pressure relief design, chemical reaction systems, and fire and explosion dynamics expert. In this regard he has provided consulting and design services, expert testimony and incident investigation support and reconstruction for a large number of clients.

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Harold G. Fisher retired as a Principal Engineer from the Process Safety Technology Group of Union Carbide Corporation after 40 years of service following the acquisition by the Dow Chemical Company. He has over 11 years of production engineering experience and 27 years reaction safety engineering / emergency relief system design experience. He earned a BSChE from Syracuse University in 1961 and MSChE, MSE (IE) and MBA degrees from West Virginia University in 1968, 1971 and 1974, respectively.

Harold has been involved with the Design Institute for Emergency Relief Systems (DIERS) since 1976 having served as Technical Chairman from 1982-1984 and Chairman of the DIERS Users Group since 1985. He is a lecturer for the AIChE Continuing Education Courses "Emergency Relief System Design Using DIERS Technology" and "Methods for Sizing Pressure Relief Vents". He was the editor and contributing author of the AIChE / DIERS Project Manual and co-editor and contributing author of two AIChE / DIERS "International Symposia on Runaway Reactions, Pressure Relief and Effluent Handling" books.

He is a Fellow of the AIChE. Upon his retirement, Mr. Fisher opened a consultancy and has entered into an exclusive alliance with Fauske & Associates of Burr Ridge, IL.

Dr. Michael A. Grolmes is president and founder of Centaurus Technology, Inc. He has over 30 years experience in multi-phase thermal hydraulics, and process safety related analysis and experiments. In 15 years at the Argonne National Laboratory, Dr. Grolmes was involved with advanced nuclear reactor safety technology, specializing in multi-phase flow applications.

On leaving Argonne, Dr. Grolmes was a founding principal of Fauske and Associates, Inc., and played a leading role in that firm's growth in chemical process safety. He served as lead project engineer for the conduct of the Design Institute for Emergency Relief System (DIERS) small and large scale test activities, and the development of the SAFIRE code.

Since 1993, Centaurus Technology has provided industrial clients with over 300 process safety evaluations. Dr. Grolmes has published over 100 technical articles on multi-phase flow and process safety. He is a member of AIChE, and NFPA, and is a current member of the DIERS Users Group providing regular technical contributions.