Three Dimensional Flow in a Linear Compressor Cascade at Design Conditions

SHUN KANG* and CH. HIRSCH**
Vrije Universiteit Brussel, Department of Fluid Mechanics
Pleinlaan 2, 1050 Brussels, Belgium

Abstract

Experimental data measured upstream, inside and downstream of a large scale linear compressor cascade with NACA 65-1810 blade profile are presented. The flow is surveyed at 15 traverse planes with 14 (in half span) x 24 (in pitch) points inside a passage, and 14 x 33 points downstream exit plane. The measurements are obtained with a small size five hole probe, and wall static pressure taps. It is observed that the three dimensional flow inside and behind the cascade is characterized, not only by the conventional aspects, such as leading edge horseshoe vortices, passage vortices, trailing edge vortex sheet and corner vortices, but also by two spiral node points, formed from the three dimensional separation lines, on suction surface, and the resulting concentrated vortices.

Nomenclature

c = blade chord
Cp = static pressure coefficient
Cpt = total pressure coefficient
l = blade span
L.E. = leading edge
PS = pressure side
Q = represent V,u,v,w,Cpt, etc.

Nomenclature

y = spanwise distance
z = pitchwise distance
ρ = density
β = pitchwise flow angle

Subscripts

i,j,k = index along x,y,z axis

Introduction

Since the realization of the importance of three dimensional flow properties in turbomachinery, research into this aspect of turbomachinery aerodynamics has been in progress for many years. Yet, many aspects and properties of the nature of secondary flows and losses remain unclear.

It is well recognized that the complexity of a cascade flow field is related directly to the generation and the evolution of various vortices, such as passage vortex, leading edge horseshoe vortex, blade trailing edge vortex and tip leakage vortex. Representative results obtained in the past are those, for example, by Langston et al. (1977), Marchal and Sieverding (1977), for turbine cascade as reviewed by Sieverding (1985), and by Lakshminarayana and Horlock (1963), and Salvage (1974) for compressor cascade. Most of the investigations on axial flow compressor flow fields have been concerned with rotor wake characteristics (Lakshminarayana and Poncet, 1974; Hirsch and Kool, 1977; Kool et al, 1978) and with the interaction region of the casing wall boundary layer, the rotor wake and the tip leakage flow (Davino and Lakshminarayana, 1982; Hunter and Cumpsty, 1982). The behaviour of flow fields inside and behind an axial rotor had been examined by Dring et al (1982, 1984). The three dimensional structure of vortices inside and behind an axial flow rotating blade row was given by Inoue and Kuroumaru (1984) according to their measurements behind the blade.

* Ph. D. Student, Permanent address: Power Engineering Dept., Harbin Institute of Technology, Harbin 150006, P. R. China
** Professor, Member ASME
Even though these works have produced a fairly detailed description of the flow mechanisms and are very helpful and instructive for improving cascade designs and numerical calculations, it seems that further work on the entire flow field of compressor cascade, especially at design condition which is even more important for designers, are needed.

The present paper intends to give more information on the secondary flow and loss mechanism which exists within and behind a linear compressor cascade with NACA 65-1810 blade profile at design conditions. It is recognized that a linear cascade cannot simulate the effects of, for example, inlet skew and rotation. Nevertheless, the present investigation can at least provide some information on the nature of secondary flow in low speed compressor and an assessment of the relative importance of such flows.

Experimental Facility

Wind tunnel The present investigations are carried out in the low speed compressor cascade wind tunnel of the Department of Fluid Mechanics, VUB. Air is driven by a blower powered with an AC motor and supplied to the test section via a row of guide vanes to adjust inlet flow uniformity, a diffuser, a settling chamber and a nozzle. The test section of the wind tunnel, as indicated in Fig.1, consists of two parallel plates, aligning horizontally between which a cascade is installed. A gap of about 3 cm, approximately equal to the thickness of the nozzle side wall boundary layers, is introduced between the two extreme blades and the nozzle side wall for removing the side wall boundary layers. Two variable flaps are placed at the exit of the two extreme blades of the cascade to assure absolute stable outlet flow conditions and to reduce the degree of non-periodicity.

Cascade geometry The cascade consists of seven NACA 65-1810 blade profiles. The aspect ratio is 1.0, chord=20 cm, solidity=1.111 and the stagger angle is 10°. The blade inlet angle is 32.5° and the outlet angle is -12.5°. Due to technological difficulties, a sharp trailing edge is avoided by the addition of a radius of 1% chord. The coordinates of the improved blade profile are given in the appendix. A single passage of the cascade and its coordinate system with y-axis along the spanwise direction is shown in Fig.2.

Probe traverse mechanism and data acquisition system In the present experiment, a five-hole probe is used to acquire three dimensional flow ahead of, within and behind the cascade. The five-hole probe, made in the Department Laboratory, is welded of five 90 mm long needles with internal diameter of 0.55 mm and external diameter of 0.8 mm, the resultant external size of the probe is 2.6 mm of the diameter and 27 mm long with an apex angle of 30°. The small 2.6 mm connected tube is fitted within a 12 mm-diameter long tube for increasing stiffness away from the sensing tip. For details, see Kang(1989). The radius of the sensitive part of the probe is small relative to the blade pitch (1.4% pitch) and to the inlet boundary layer thickness (6.5% of the inlet boundary layer thickness). The five small tubes are connected to a scanivalve through five long and flexible plastic tubes and share one pressure transducer. The pressure differences sensed by the transducer are converted into electronic digital signals through a strain gage conditioner, and transferred to an oscilloscope. The wave form on the oscilloscope screen is recorded through a bus controller by a microcomputer in which the voltage readings of the waveform are averaged and transformed into pressure values.

The five hole probe is mounted on a support which is located downstream and fixed to the upper wall of the cascade, from which the probe can be inserted, toward upstream, into the flow field to be measured. The support system enables the probe to move in any axialwise, spanwise and pitchwise directions inside the cascade passage with the help of three step motors mounted on the system. The three step motors are connected to a stepmotor controller and a computer through the bus controller. With this system the probe can be placed in any desired position inside the passage of the cascade, except for the regions immediately ahead of the blade leading edges. The mechanical resolution of the device is about 0.05 mm for both spanwise and pitchwise directions of the cascade.

The traverse measurements are conducted in the third passage counted from the right(Fig.1). There are 15 traverse planes from 7.5% chord upstream of the leading edge plane to 25% chord downstream of the cascade exit plane, as shown in Fig.2 at a spanwise height. In each of the traverse planes 24 stations from suction side to pressure side inside the passage and 33 stations behind the cascade. Fourteen points in each station are detected from near endwall to midspan. The measured points near the walls, including blade surface and endwall, on each traverse plane are located 2 mm away from the walls. During the measurements the data acquisition is carried out station by station (from endwall to midspan or from midspan to endwall) on each traverse plane.

Wall static pressures, including blade surfaces(suction surface and pressure surface) and endwall are also recorded by static pressure tubes. The tapings on both sides of the blade, the middle blade in Fig.1, are put in three section along 1.5%, 15% and 50% of span and 13 locations distributed from near leading edge(6% on suction side and 1% on pressure side) to trailing edge. Due to the physical constraint of the blade section, the taps on the blade surface can not be set as near the trailing edge as desired(12% upstream of the trailing edge on both surfaces). In order to get information on the extreme leading edge flow, a tap was set there at midspan. The locations of the static pressure taps on hub endwall are shown in Fig.2. Besides, a conventional pitot-tube is placed at 40% chord upstream of the leading edge plane, from where the inlet conditions are obtained.

Measurement accuracy The five hole probe is fully calibrated in a jet, Kang(1989). In order to increase the measurement precision, the same data acquisition and control system are used in the calibration and the present cascade measurements. The accuracies of
the measured velocity and total pressure are 1% of the inlet midspan values from where all the reference parameters are taken. The uncertainty of the measured flow direction is better than 1°.

**Test conditions** All of the tests in the current investigation are conducted with the inlet flow velocity being kept constant (23.7 m/s). Whenever the velocity is varied, normally decreased, about 1% due to the accumulation of dirt on the grid in front of the guide vanes, the grid is cleaned. The test Reynolds number, based on the inlet velocity and blade chord is about $2.9 \times 10^5$. The free stream turbulence intensity is 3.4%.

The mass-averaged air inlet and exit angles, measured 40% chord upstream, and 25% chord downstream are 29.3° and -2.5°, compared to design values of 30° and -4.02°, respectively.

**Analysis Methods**

**Definition of secondary flow** In the present analysis of the linear compressor cascade, the pitchwise local flow directions at midspan are used to determine the secondary flow vectors at the other spanwise coordinates. Secondary flow vectors are calculated by projecting onto the plane normal to the flow direction at midspan.

A secondary flow coordinate system ($x_s, y, z_s$) is introduced as shown in Fig.3. The secondary flow velocities are defined by the following formula

$$w_s = (u^2 + w^2) \sin \theta; \quad v = v$$

where $\theta$ is the flow skewing angle.

For the presentation, the secondary flow vector is turned around the y(or z)-axis until it lies in the measuring plane such that the secondary velocities charts show the real secondary flow and not the projection of the secondary flow velocity from the $x$-$y$ plane onto the measuring plane.

![Fig.3 Secondary flow coordinate system](https://example.com/image3.png)

The velocities are all normalized by the inlet velocity $V_1$. The tangential distances are normalized by the pitch, while the axial and spanwise coordinate $x$ and $y$ are normalized with the blade chord and the blade height, respectively.

**Results**

1) **Inlet Flow**

The velocity profiles of the incoming endwall boundary layer are obtained at 40 percent chord upstream of the cascade leading edge plane ($x/c=1.40$) for two pitchwise positions $z=30$ mm and 100 mm to show the pitchwise uniformity in Fig.4. It is seen from these results that the upstream boundary layer is turbulent with a shape factor $H$ of about 1.22 and a displacement thickness $\delta'$ over chord of 0.0014.

![Fig.4 Inlet velocity profile](https://example.com/image4.png)

2) **Wall Static Pressure Distributions**

The static pressure distributions on the blade surfaces in three spanwise positions are given in Fig.5. The data close to the trailing edge shown in Fig.5 are obtained on the traverse plane No.11. The differences between the pressure values, especially on the suction side, in spanwise direction will result in the defect of blade force due to the existence of the endwall boundary layer. The changes of the blade boundary layer or static pressure distributions along the blade surface near the endwall will directly influence the position and the strength of the passage vortex (or secondary flow) which will be discussed in the following section.

**Pressure surface (PS)** At the leading edge, the small incidence angle (-2.5°) results in a strong acceleration which leads to a region of laminar flow. The boundary layer undergoes a mild adverse pressure gradient in the following short interval between 1% - 5.5% chord. In the region from 40 percent chord to 50 percent chord downstream, the flow is again subjected to a mildly adverse gradient. It can be inferred according to the pressure distribution that the process of the boundary layer transition may take place over a long distance. The subsequent stronger adverse pressure gradient will make the eventual complete transition to turbulence. By reading the anemometer signals of hot wire at midspan, it is found that the onset of the pressure side boundary layer transition may be at about 11% chord downstream of the leading edge.

It is also be seen from Fig.5 that near midspan the leading edge stagnation points are located on the pressure side. Near the endwall, however, the stagnation points move toward the leading edge under the action of the transverse pressure gradient near the leading edge (see Fig.7).

![Fig.5 Static pressure distributions on blade surface](https://example.com/image5.png)
Suction surface (SS) Starting from the leading edge of the suction surface, the flow is accelerated and the boundary layer flow remains in laminar state under the effect of the strong favourable streamwise pressure gradient, until the low pressure point at about 15% chord. Immediately downstream of the minimum pressure point the adverse pressure gradient is so strong that the laminar boundary layer may separate. The separated laminar free shear layer then transits into a turbulent shear layer. A laminar separation bubble or transition bubble is generated, followed by turbulent reattachment at 40% chord. This conjecture can be inferred from the small adverse pressure gradient, or pressure plateau, in the region between 30–40% chord. With the three dimensional flow conditions the bubble may extend in the spanwise direction. Downstream of the reattaching point the turbulent boundary layer moves in an adverse pressure gradient. It will be seen in the following section that the turbulent boundary layer may separate near the trailing edge.

The conclusions on the development of the blade surface boundary layer mentioned above were confirmed with a hot-wire to see the turbulent levels (Fig. 6) at different chordwise positions at midspan near the blade surfaces. It is seen that the turbulent levels in the laminar region remain the same as that in the free stream region, while around the transition point the turbulent level increases quickly, and after which it decreases but still much higher than that in the free stream.

Endwall The static pressure contours at the endwall is given in Fig. 7. In the front of the blade leading edge, the streamwise pressure gradient is favourable near the suction side, but is adverse in the pressure side. The adverse pressure gradient ahead of the pressure side leading edge, with the stagnation point located at the leading edge of the pressure surface as mentioned above, will cause the endwall boundary layer to separate and, as a result, a horseshoe vortex is formed in the corner of the blade surface / endwall, which will be observed from the traverse data in the following. A minimum pressure point exists on the suction side about 25% chord downstream of the leading edge.

Fig. 7 Contours of endwall static pressure

Fig.6 Turbulent intensity distribution along blade surfaces

Fig.8 Secondary velocity vectors on the transverse planes, a) No.2, b) No.9, c) No.11, d) No.12 and e) No.15
3) Secondary Flows and Total Pressure Losses

Upstream and inside blade passage A general view of the production and development of secondary flows and total pressure losses from 7.5% to 25% chord downstream of the outlet plane are discussed in this section. Fig. 8 shows the secondary flows and Fig. 9 shows the losses at some of the traverse planes, see Kang(1990) for details. The secondary flow in planes No.1 (7.5% c upstream of the leading edge) and No.2(Fig.8)(leading edge plane) show two small size vortices rotating in opposite sense at the corners of the suction side (SS) / hub endwall, and the pressure side (PS) / hub endwall. This show that the incoming turbulent boundary layer is separated under the action of the adverse pressure gradient on the endwalls in front of the pressure side leading edge(Fig.7) when approaching the blade leading edge with an incidence of 2.5° (or an angle of attack of 29.3°), and the so-called horseshoe vortex is formed.

Because of the existence of transverse pressure gradient inside the passage, the suction side leg of the horseshoe vortex is weakened, when stretching forward along the corner of suction surface / hub endwall over planes No.3 and No.4), and become unnoticeable downstream of the minimum pressure point in front of plane No.5(Fig.8) till the trailing edge. The pressure side leg vortex, however, is enlarged and moves to midpitch when it stretches to the trailing edge and is engulfed into the so-called passage vortex. In the present flow conditions, it is difficult to separate one from the other. Hence, in the following discussions the nomenclature, passage vortex partly include the pressure side leg of the leading edge vortex.

The approximate positions, defined as the rotation centre(Fig.8), of the passage vortex core in each traversed plane from inlet to exit are listed in Table 1. The passage vortex gradually moves away from the pressure side up to plane No.7 and then bends towards the pressure side in the region around x/c = 0.34(plane No.8), which corresponds to the changes of the suction surface static pressure distribution from a pressure plateau to a large adverse pressure gradient. Then the vortex moves again to the suction side in its subsequent development, and near the exit plane it stretches along midpitch .

Table 1 Coordinates of Passage Vortex

<table>
<thead>
<tr>
<th>$x$/c</th>
<th>0.05</th>
<th>0.06</th>
<th>0.06</th>
<th>0.14</th>
<th>0.15</th>
<th>0.15</th>
<th>0.15</th>
<th>0.14</th>
<th>0.13</th>
<th>0.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y$/c</td>
<td>0.88</td>
<td>0.86</td>
<td>0.76</td>
<td>0.72</td>
<td>0.60</td>
<td>0.56</td>
<td>0.56</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The total pressure loss coefficient contours (some of which are shown in Fig.9) from inlet to traverse plane No.5 are almost uniform over the whole pitch, except near the suction side endwall. The feature of the loss contours near suction side may correspond to the evolution and the disappearance of the suction side leg of the leading vortex and to the intersection of the separation line of the pressure side leg horseshoe vortex with the suction surface. Downstream of traverse plane No.6, the high loss region near suction side gradually moves far away from the endwall, which indicate the spanwise movement of the three dimensional separation line (see following) on suction surface. Under the action of the passage vortex, the low energy fluids in pressure surface boundary layer and in the pressure side of the endwall boundary layer have been swept away toward the suction surface. As a result, the boundary layer on the pressure side decreases with axial distance. On the contrary, the suction side end wall boundary layer increases with axial distance.

Near blade surfaces The flow near the pressure side is basically two dimensional, but it is more complex near the suction surface. Fig.10 shows the total pressure contours and flow velocity vectors on the S2 surface near the suction surface. The dominant feature of the flow field on the blade suction surface is the existence of the three dimensional separation line, an asymptote of the limiting streamlines. The asymptote of the streamlines on the suction surface, starting from 30%c near endwall and moving outward as it stretches to downstream, represents the separation line of the passage vortex. As mentioned above, the pressure side leg horseshoe vortex has merged into the passage vortex, the separation line on suction surface may be originated from the leading edge endwall. From the velocity vectors on the blade to blade surface($S_b$ surface) (Kang,1990) near the end wall, however, the separation line associated with the leading edge horseshoe vortex is unnoticeable. The reason may be that the leading edge vortex is not strong enough; and the detection in the present study is not close enough (2 mm away from wall) to the wall for the constraint of the probe size.

The accumulation of the low energy fluid along the three dimensional separation line on suction surface can be clearly observed from the contour (Fig.10) of the total pressure loss on the S2 surface near suction side. The flat part of the total pressure isolines near the endwall downstream of the leading edge again indicates the evolution of the suction side leg vortex. The point, after the flat part, downstream of which the isolines go up, is related with the
intersection of the separation line of the pressure side leg horseshoe vortex with the suction surface.

As the separation line stretches outward and downstream along the suction surface, it changes its direction and moves inward near the trailing edge under the action of the strong adverse pressure gradient in the appropriate region. The only possibility of the flow trailing edge under the action of the strong adverse pressure gradient in the appropriate region. The only possibility of the flow development is a spiral node point formed (see Fig. 12). From the secondary flow velocity vector plot on plane No. 11 (Fig. 8), it is observed that the flow near the pressure side moves towards the pressure surface within the region of 30% span. This implies that the fluid on the pressure surface moves up round the blade trailing edge and then toward the spiral node point along the suction surface. The axial and tangential velocity components near the blade suction surface in transverse plane No. 11 and those immediately downstream of the trailing edge in transverse plane No. 12 are given in Fig. 11. It is clearly seen from the axial velocity distributions that reverse flows exist in the region upstream and immediately downstream of the trailing edge. This evidence again proves that a spiral node should be formed somewhere on the suction surface near the trailing edge. The tangential velocity near suction surface in plane No. 11 shown in Fig. 11 indicates that there is an injecting flow at 13% span from the suction surface to the main flow with a velocity almost equal to the midspan tangential velocity, which is characterized by the nearly zero value on the tangential velocity profile. The flow feature can also be observed from the chart of the secondary flow vector in plane No. 11 in about y/l=0.13 where a spiral node point, coming partly from the endwall and the suction surface boundary layers along the separation line on the suction surface, and partly from the pressure surface boundary layer by-passing the trailing edge and from the blade wake, detach from the point and inject into the main flow field. As a result of it, a concentrated vortex, rotating in a sense opposite to the passage vortex, is formed around the spiral point. This vortex is named here as 'concentrated shed vortex', using 'shed' as it is shed from the suction side leg of the leading vortex which has a very small size in the region between 20% c to trailing edge and can not be detected with the present probe. Outside of the passage, the constraints of blade surface are released suddenly, its size grows and become visible from transverse plane No. 12, located 2 mm downstream of the trailing edge; (b) it is originated from trailing shed vortex sheet and intensified by the interaction of the blade and hub endwall boundary layers. By closely inspecting the spanwise velocity profiles in the wake on the traverse plane No. 12 (Kang, 1990), it is found that symmetric outflow profiles exist in 2–5% span, above the corner vortex. Hence, it is probable that the corner vortex may be associated with the suction side leg of the horseshoe vortex. Because of the existence of the corner vortex, the skew of the wake centre line in Fig. 9 shows that the amount of overturning caused by the passage vortex is reduced very close to the endwall.

Where and how is this corner vortex generated? Two probabilities may exist: (a) because the rotation sense of this vortex is the same as the suction side leg of horseshoe vortex, it probably is the evolution of the suction side leg of the leading vortex which has a very small size in the region between 20% c to trailing edge and can not be detected with the present probe. Outside of the passage, the constraints of blade surface are released suddenly, its size grows and become visible from transverse plane No. 12, located 2 mm downstream of the trailing edge; (b) it is originated from trailing shed vortex sheet and intensified by the interaction of the blade and hub endwall boundary layers. By closely inspecting the spanwise velocity profiles in the wake on the traverse plane No. 12 (Kang, 1990), it is found that symmetric outflow profiles exist in 2–5% span, above the corner vortex. Hence, it is probable that the corner vortex may be associated with the suction side leg of the horseshoe vortex. Because of the existence of the corner vortex, the skew of the wake centre line in Fig. 9 shows that the amount of overturning caused by the passage vortex is reduced very close to the endwall.
tangential velocity downstream of the trailing edge in traverse plane No. 12 (Fig. 11), on which the tangential velocity change signs at 2% span and 30% span.

The centre line of the wake (Fig. 9) becomes distorted as the fluid rotates. This distortion is just noticeable on the total pressure loss contours in the downstream traverse planes. The regions of underturning and overturning which are due to the presence of the vortices mentioned above can be identified by this distortion.

**Secondary flow structure** In summary, the structure of the compressor cascade secondary flow, inferred from the discussions mentioned above is shown in Fig. 12. The incoming boundary layer flow separates in front of the blade leading edges and forms a horseshoe vortex. Under the action of the passage traverse pressure gradient, the suction side leg of the horseshoe vortex is convected to the corner of the suction surface/endwall, when it stretches toward downstream.

The pressure side leg of the horseshoe vortex, however, is engulfed into the passage vortex during its evolution from the leading edge to downstream, since it rotates in the same sense as the passage vortex. The passage vortex gradually moves away from the pressure side to midpitch from the leading edge plane to about 30% chord downstream, and then turns toward the pressure side in the axial region corresponding to the variation of the static pressure distribution along the suction surface from a pressure plateau to a large adverse pressure gradient. In its subsequent development, the vortex moves again toward suction side, and then remains in midpitch stretching to the exit plane. In spanwise direction, the passage vortex moves up from the leading edge plane with the increase of the traverse pressure gradient. Downstream of the lower pressure point on the suction surface, it remains at constant height over a short distance, which is associated with the flat portion of the suction surface pressure distribution. With the reduction of the traverse pressure gradient the vortex moves downstream of the midchord and then remains horizontal from about 30% upstream of the trailing edge.

Inside a blade wake, there are two discrete vortices and a vortex sheet, rotating in same sense, but opposite to the passage vortex. The vortex sheet may be the classical trailing edge vortex, i.e., trailing shed vortex and trailing filament vortex. The corner vortex may be the evolution of the suction side leg of the leading edge vortex. The concentrated shed vortex, named by the authors, is originated from the spiral node point formed by the separation lines on the suction surface. As it stretches downstream, the concentrated shed vortex may engulf the trailing vortex filaments close to it. But, originally, it is not formed by the trailing shed vortex and trailing filament vortex. The separation line, coming from the endwall may be originated at the saddle point on the leading edge endwall.

**Conclusions**

The nature of the development of the secondary flows and total pressure losses which exist in a linear compressor cascade has been investigated. As expected, the general nature of the three-dimensional flows are closely related with the generations and the evolutions of the various vortices occurring inside and behind the passage, and within the wake. The traces of the passage vortices, which dominate the secondary flow and the distribution of energy loss, are directly dependent on the blade surface pressure distribution profile. The vortices observed from the fairly detailed quantitative data presented in the paper, except for the well known vortices, such as the horseshoe, the passage, corner vortices and trailing vortex sheet, are the concentrated vortices, shed from the spiral node points on the suction surface near trailing edge. Because the existence of the concentrated shed vortices and the corner vortices, and the interactions of them with the passage vortices, the wake centre lines are seriously skewed, which makes a reduction of the amount of overturning, caused by the passage vortices, in the appropriate region. Due to the physical constraint, the information on the immediate vicinity of the blade leading edge, and the corner of blade surfaces and endwall is missed.

**References**


Kang, S., 1990. Three Dimensional Flows in a Linear Compressor cascade at design conditions. Research report of Fluid Mechanics Department, VUB.


Appendix

**Blade Profile Coordinates**

<table>
<thead>
<tr>
<th>Chordwise</th>
<th>S. S.</th>
<th>P. S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.0000</td>
<td>2.4440</td>
<td>-0.6440</td>
</tr>
<tr>
<td>1.5000</td>
<td>3.1240</td>
<td>-0.6040</td>
</tr>
<tr>
<td>2.5000</td>
<td>4.2640</td>
<td>-0.4120</td>
</tr>
<tr>
<td>5.0000</td>
<td>6.4960</td>
<td>0.2000</td>
</tr>
<tr>
<td>10.0000</td>
<td>10.0420</td>
<td>1.3340</td>
</tr>
<tr>
<td>15.0000</td>
<td>12.9260</td>
<td>2.3380</td>
</tr>
<tr>
<td>20.0000</td>
<td>15.3860</td>
<td>3.2260</td>
</tr>
<tr>
<td>30.0000</td>
<td>19.4460</td>
<td>4.7820</td>
</tr>
<tr>
<td>40.0000</td>
<td>22.6140</td>
<td>6.0420</td>
</tr>
<tr>
<td>50.0000</td>
<td>25.1160</td>
<td>7.1040</td>
</tr>
<tr>
<td>60.0000</td>
<td>27.0160</td>
<td>7.9760</td>
</tr>
<tr>
<td>70.0000</td>
<td>28.3880</td>
<td>8.6920</td>
</tr>
<tr>
<td>80.0000</td>
<td>29.2700</td>
<td>9.2860</td>
</tr>
<tr>
<td>90.0000</td>
<td>29.6360</td>
<td>9.7840</td>
</tr>
<tr>
<td>100.0000</td>
<td>29.4780</td>
<td>10.2300</td>
</tr>
<tr>
<td>110.0000</td>
<td>28.9700</td>
<td>10.4500</td>
</tr>
<tr>
<td>120.0000</td>
<td>27.9700</td>
<td>10.5860</td>
</tr>
<tr>
<td>130.0000</td>
<td>26.5040</td>
<td>10.5760</td>
</tr>
<tr>
<td>140.0000</td>
<td>24.6080</td>
<td>10.3840</td>
</tr>
<tr>
<td>150.0000</td>
<td>22.2780</td>
<td>9.9420</td>
</tr>
<tr>
<td>160.0000</td>
<td>19.5020</td>
<td>9.1540</td>
</tr>
<tr>
<td>170.0000</td>
<td>16.2840</td>
<td>7.9440</td>
</tr>
<tr>
<td>180.0000</td>
<td>12.5260</td>
<td>6.0860</td>
</tr>
<tr>
<td>190.0000</td>
<td>8.1000</td>
<td>3.2760</td>
</tr>
<tr>
<td>199.0000</td>
<td>2.6000</td>
<td>0.0500</td>
</tr>
<tr>
<td>199.5000</td>
<td>2.1500</td>
<td>0.3500</td>
</tr>
<tr>
<td>200.0000</td>
<td>1.1500</td>
<td>1.1500</td>
</tr>
</tbody>
</table>

L.E. Radius 1.374