Saturn-V sound levels: A letter to the Redditor

Kent L. Gee, Logan T. Mathews, Mark C. Anderson, et al.

Citation: The Journal of the Acoustical Society of America **152**, 1068 (2022); doi: 10.1121/10.0013216
View online: https://doi.org/10.1121/10.0013216
View Table of Contents: https://asa.scitation.org/toc/jas/152/2
Published by the Acoustical Society of America

JASA ARTICLE

Saturn-V sound levels: A letter to the Redditor[a)]

Kent L. Gee,[b)] Logan T. Mathews, Mark C. Anderson, and Grant W. Hart
Department of Physics and Astronomy, Brigham Young University, Provo, Utah 84602, USA

ABSTRACT:
The Saturn V is a monument to one of mankind's greatest achievements: the human Moon landings. However, online claims about this vehicle's impressive acoustics by well-meaning individuals are often based on misunderstood or incorrect data. This article, intended for both educators and enthusiasts, discusses topics related to rocket acoustics and documents what is known about the Saturn V's levels: overall power, maximum overall sound pressure, and peak pressure. The overall power level was approximately 204 dB re 1 pW, whereas its lesser sound pressure levels were impacted by source size, directivity, and propagation effects. As this article is part of a special issue on Education in Acoustics in *The Journal of the Acoustical Society of America*, supplementary Saturn V-related homework problems are included.[1]
https://doi.org/10.1121/10.0013216

(Received 20 December 2021; revised 14 June 2022; accepted 12 July 2022; published online 23 August 2022)

[Editor: Preston Scot Wilson] Pages: 1068–1073

I. INTRODUCTION

On 16 July 1969, a Saturn-V launch vehicle lifted off from Florida's Kennedy Space Center (KSC), carrying three astronauts to the Moon. The historic Apollo 11 mission capped more than a decade of unprecedented space vehicle research and development that included rocket acoustics because of potential noise-related risks to payloads, vehicle, launch pad structures, and beyond. Many early studies (e.g., Cole *et al.*, 1957; Mayes *et al.*, 1959; Potter and Crocker, 1966) examined noise from rockets of various sizes and other supersonic jets to develop a fundamental understanding and scalings. Other early rocket noise research has been described by Lubert (2018). Additionally, McInerny (1992) and Lubert *et al.* (2022) provide reviews of the current understanding of rocket noise source physics.

The Apollo launches and the Saturn V have captured the imagination of space enthusiasts for decades. The vehicle, shown as an exploded diagram in Fig. 1, generated 34.8 MN (7.8 million lbf) of thrust at liftoff. For reference, a liftoff-thrust comparison with other historical, current, and pending/future vehicles is shown in Table I.

Given the immense thrust of the five F-1 engines that powered the Saturn-V S-1C first stage, a natural question is asked: What were the Saturn V's sound levels during launch? This question is of more than historical interest. Understanding the noise from the Saturn V provides insights into expected acoustical environments of the NASA Space Launch System and SpaceX Starship (Super Heavy), both of which may outstrip the Saturn V for the most powerful rocket ever successfully launched. Additionally, these kinds of sound levels capture the interest of acoustics students of all levels, and their documentation provides information for classroom examples and homework exercises. (See several homework problems that are included as supplementary material.[1])

This article describes what is known about the Saturn-V sound levels, as part of a special issue on Education in Acoustics in *The Journal of the Acoustical Society of America*. This is done in part to help bring together information from diverse, relatively hard-to-locate historical sources, for the acoustics educator and the launch vehicle noise researcher. However, an additional purpose is to provide a form of acoustics outreach by combatting rampant misinformation about Saturn-V acoustics that has been widely propagated through online discussion forums. The article derives its title from one such forum, Reddit.

II. ONLINE DESCRIPTIONS OF SATURN-V ACOUSTICS

A review of online forums and discussion boards yields a cacophony of claims about Saturn-V acoustics. Often, incredible statements about the acoustic energy emitted by the vehicle are repeated with no apparent root source. Such claims include that the sound level was so great that the acoustic energy could "melt concrete" and "light grass ablaze over a mile away." More concerning statements include apocalyptic presuppositions about the sound being so powerful it would "ignite the hair of bystanders" and "blast rainbows from the sky." Such claims elicit awe at the power of the vehicle that propelled humans to the Moon but are nevertheless based on a flawed understanding of the true acoustic environment.

This awe is appropriately enhanced by videos, such as Mm. (1), which contains NASA footage of the nighttime Apollo 17 launch. The combination of a humid atmosphere and backlighting allow sound waves to be seen shortly after

[a)]This paper is part of a special issue on Education in Acoustics.
[b)]Electronic mail: kentgee@byu.edu

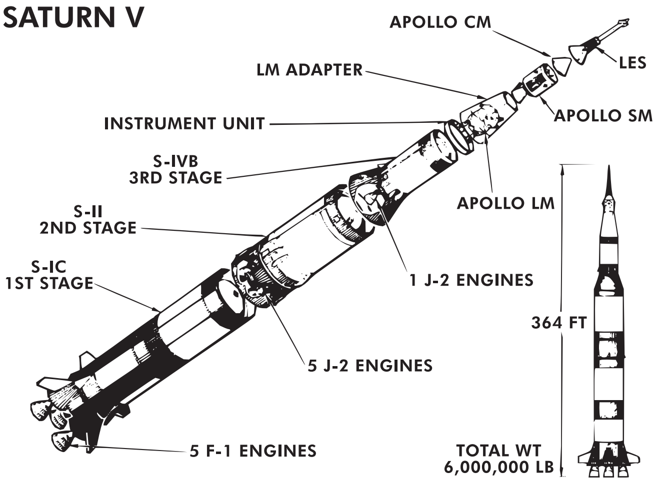

FIG. 1. An exploded view of the Saturn V, including the Boeing S-1C first stage with its five Rocketdyne F-1 engines. Reproduced and enhanced from NASA documents, retrieved online.[2] Note that many other sources show the total height of the Saturn V as 363 ft.

engine ignition. Using the vehicle height as a ruler (assumed to be 363 ft or 111 m), the speed of these visible waves is approximately 340 ± 10 m/s, consistent with acoustic propagation. Wavelengths range from about 15 to 22 m, leading to characteristic frequencies of about 15–20 Hz, consistent with measured Saturn-V spectra (McInerny, 1992).

Mm. 1. Footage of the Apollo 17 nighttime launch during which radiated sound waves are visible. This video was adapted from Discovery Channel's digitization of NASA launch footage as part of its 2008 documentary, "When We Left Earth: The NASA Missions." This is a file of type "mp4" (2.2 MB).

Some online assertions reside in the realm of science-fiction speculation; however, other confusion results when well-meaning individuals weigh in on the launch acoustics details without fully understanding the topics they are discussing. The result is a mixture of claims, backed up by an assortment of "scientific" justifications and rebuttals. Often, these claims represent a misunderstanding of fundamental acoustics concepts or simply confusion between closely related ideas. In this article, we address many of these ideas to, hopefully, give the educator and others the ability to definitively answer such questions as "Will a sound pressure level of 165 dB really ignite your hair?" and "Is the crackle heard in rocket launch noise caused by vacuum clipping?"

III. OVERALL SOUND POWER LEVEL

The first acoustic quantity of interest is the total acoustic power, W. The power is a source property, not directly an acoustic field characteristic, which is where some of the internet confusion occurs. The overall sound power level (OAPWL) is expressed in dB re 1 pW. Note that the reference sound power in the United States changed from 10^{-13} to 10^{-12} W (1 pW) in the early 1960s (U.S. Department of the Army, 1968), which may cause some confusion in interpreting historic rocket sound power levels. These changes during the height of Saturn-V development serve as an important reminder to make clear the decibel reference being used.

Tied to the idea of OAPWL is acoustic efficiency, the ratio between a radiator's acoustic power and mechanical power, W_m; efficiency is usually expressed as a percentage. Historically, the acoustic efficiency of rockets has been believed to be around 0.5% (see Eldred, 1971 and discussion by Lubert *et al.*, 2022). A recent calculation from Falcon-9 measurements yielded an efficiency of ∼0.31% (Mathews *et al.*, 2021). According to McInerny (1996a), the mechanical power is $W_m \approx 0.5TU_e$, where T is the engine's thrust and U_e is the gas exit velocity. These relationships enable an immediate estimate of W and OAPWL. Assuming that the F-1 engine has an exit velocity of 2.6 km/s (as calculated from its specific impulse), the Saturn V's $W_m = 45.2$ GW. With an acoustic efficiency of 0.5%, $W = 226$ MW and OAPWL = 203.5 dB re 1 pW. Given reasonable uncertainty in U_e, the Saturn V's OAPWL can be estimated to be 203–204 dB re 1 pW.

Based on this physical model for sound power generation, the power levels of 220 and 235 dB reported in various locations online are simply nonphysical; 220 dB re 1 pW implies an efficiency of 25%, and 235 dB is greater than the total mechanical power of the vehicle, converted to a level (226 dB re 1 pW). In fact, 235 dB represents the OAPWL

TABLE I. A comparison of several heavy and super heavy-lift space vehicles by thrust and number of successful orbital launches as of this article's publication. TBD, to be determined.

Vehicle	Developer	Liftoff-thrust (MN)	Number of orbital launches	Launch years
Starship (Super Heavy)	SpaceX (USA)	72.0	—	TBD
N1	USSR	45.4	0 (4 failures)	1969–1972
Space Launch System	NASA	39.1	—	TBD
Saturn V	**NASA**	**34.8**	**13**	**1967–1973**
Energia	USSR	34.8	1 (+1 suborbital)	1987–1988
Space Transportation System (Shuttle)	NASA	30.2	134	1981–2011
Falcon Heavy	SpaceX (USA)	22.8	3	2018–Present
New Glenn	Blue Origin (USA)	17.1	—	TBD
Ariane V	ESA (Europe)	15.2	112	1996–Present
Long March V	China	10.6	7	2016–Present
Delta IV Heavy	ULA (USA)	9.4	13	2004–Present

produced by the simultaneous launching of over 1400 Saturn Vs with an acoustic efficiency of 0.5%.

Actual measurements on the Saturn-V first stage bear out the sound power 203–204 dB prediction. Figure 2 shows the power level spectrum from S-1C static test measurements (Kramer, 1966), along with the integrated OAPWL. (Kramer, 1966, reported 213 dB re 10^{-13} W.) Allgood (2012) reports an OAPWL of 204 dB re 1pW for the S-1C (with an actual datapoint that suggests 203.7 dB) from NASA Stennis Space Center testing. Thus, reported measured levels and predictions based on acoustic efficiency arguments indicate levels of 203–204 dB re 1 pW for the Saturn V, far lower than some widely circulated online reports. The effects of plume deflection on the noise source or ground reflections on the measurement remain topics of needed research.

IV. ROCKET NOISE SOURCE CHARACTERISTICS

In some online forums, correct OAPWL values have been cited, using Allgood (2012), but commenters are then led astray by misunderstanding differences between the OAPWL and the overall sound *pressure* level (OASPL). Before turning to a discussion of Saturn-V sound pressure levels, some information regarding the source extent and directivity is important to establish proper physical reasoning.

A rocket plume generates its noise from turbulence that requires some distance to fully develop; the noise does not originate from the nozzle exit but rather at some distance downstream. Our best understanding of a rocket plume's dominant axial source region (see discussion and references in Lubert *et al.* (2022)) is that it extends from approximately 10 to 30 nozzle exit diameters, D_e, with the maximum source region occurring $\sim 17\,D_e$ downstream of the nozzle. How does this translate into physical distances for the Saturn V? Given the F-1 $D_e = 3.76$ m and relatively close clustering of the five F-1 nozzles, their exhaust plumes effectively merge into a single plume with an effective exit diameter, $D_{e,\mathrm{eff}} = D_e\sqrt{5} = 8.41$ m. Using $D_{e,\mathrm{eff}}$, the noise source region for the undeflected S-1C plume extends from 80 to 250 m downstream of the nozzle exit plane. Given the Saturn V's $\sim$111 m (363 ft) height, the dominant undeflected plume noise source after lift-off ends more than two vehicle lengths behind the rocket.

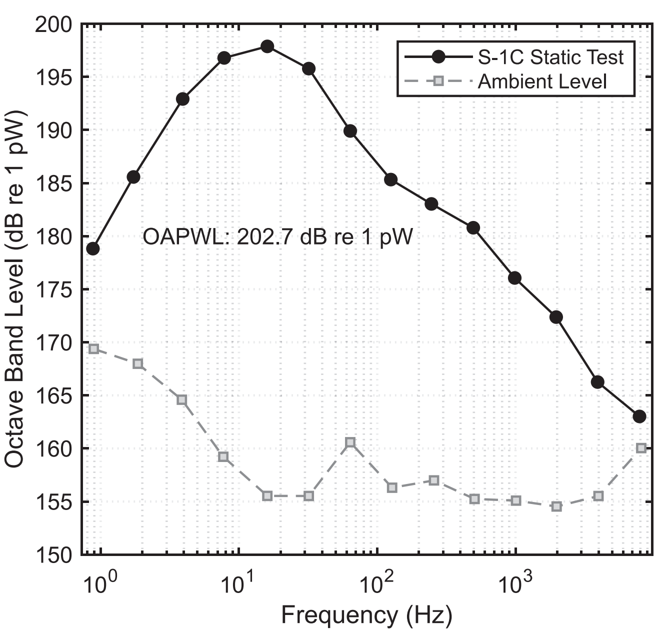

FIG. 2. The sound power and ambient level spectra, along with the OAPWL calculated from spectral integration. Adapted from Fig. 1 of Kramer (1966), including a change of decibel reference from 10^{-13} to 10^{-12} W. The ambient levels indicate a positive signal-to-noise ratio for each frequency band.

The large radiating source area implies that the sound pressure levels are much lower than those from a monopole with equal OAPWL. However, partial source coherence and radiated noise directionality increase rocket sound levels at some angles. Supersonically convecting, large-scale turbulent structures in the plume give rise to radiated Mach waves, whose average radiation angle depends on the turbulence convection speed and ambient sound speed. For typical rocket conditions, these Mach waves produce a broad radiation lobe at a peak angle of $\sim 65°–70°$ relative to the plume downstream axis with a maximum directionality enhancement (peak directivity index) for OASPL believed to be about 8 dB (McInerny, 1996a; Cole *et al.*, 1957).

The combined effects of source extent and directivity on OASPL relative to OAPWL are captured by an expression for the maximum OASPL, $\mathrm{OASPL_{Max}}$, adapted from McInerny (1996a). Using her assumed 8 dB peak maximum directivity index (i.e., in the maximum radiation direction), the $\mathrm{OASPL_{Max}}$ at radius, R, from a source with spherical spreading can be written as

$$\mathrm{OASPL_{max}} = \mathrm{OAPWL} - 10\,\log_{10}(4\pi R^2) + 8, \quad (1)$$

with an implied reference radius of 1 m. In Eq. (1), the minimum observer radius will increase with source size because the observer must be outside the source, decreasing $\mathrm{OASPL_{max}}$ relative to OAPWL. On the other hand, a directional source will increase $\mathrm{OASPL_{max}}$. Equation (1) was used by Mathews *et al.* (2021) to compare measured and OAPWL-predicted $\mathrm{OASPL_{Max}}$ for Falcon-9 launches, resulting in a difference of only 1 dB.

V. SOUND PRESSURE LEVELS

Given this understanding of a rocket's source characteristics that the radiated pressure field will result in average levels significantly lower than the OAPWL, what are expected pressure levels? When discussing measured sound levels from a rocket—and this has led to some confusion online—some care must be taken to distinguish between time-averaged levels, such as OASPL, and instantaneous levels, such as peak level instantaneous sound pressure levels. This section describes expected levels for both quantities.

A. Maximum overall sound pressure levels

In the public literature, relatively little information exists about $\mathrm{OASPL_{Max}}$ at Saturn-V observer locations.

Thankfully, McInerny (1992) showed some near and mid-field data from Apollo missions contained in presently unavailable KSC reports. The octave-band spectra at the times of maximum received level have been digitized to produce Fig. 3 and calculate $\mathrm{OASPL_{Max}}$ at different horizontal distances from the launch platform: 81.5 (average of two nearest measurement locations), 183, and 366 m (9.7, 21.8, and 43.5 $D_{e,\mathrm{eff}}$). Given these are the only measured Saturn-V pressure data we were able to find, some validation is appropriate. How do these levels compare to modern measurements of other rockets?

Historical and recent literature indicate that these measured $\mathrm{OASPL_{Max}}$ values for the Saturn V are well within reasonable bounds for a rocket. Rockets of a variety of sizes have shown maximum levels of 156–158 dB at offset distances of about 17–18 D_e from the plume centerline. (A reference pressure of 20 μPa is used for all pressure levels.) These included a small solid-fuel rocket (Potter and Crocker, 1966), a GEM-60 booster (Gee *et al.*, 2009), and a Space Shuttle Reusable Solid Rocket Motor (Kenny *et al.*, 2009), which produced one-third of the Saturn V's thrust. For comparison with the Saturn V, and assuming spherical spreading from a monopole at the centerline, geometric spreading from 18 to 21.8 $D_{e,\mathrm{eff}}$ represents a 1.6 dB reduction in level. In other words, an OASPL of 155 dB at the Saturn-V 183 m measurement location is realistic.

Searching the publicly available literature did not uncover measured Apollo far-field sound levels. However, predicted levels are shown in two reports. First, Wilhold *et al.* (1963) used their launch noise model, which included vehicle motion effects, atmospheric absorption, and an empirical model for source directivity, to predict the maximum octave-band level Saturn-V noise spectrum at a range of 11.2 km. This resulted in a predicted peak (octave) frequency of 16 Hz—in line with the measured peak frequencies in Fig. 3 and the video analysis of Mm. (1)—and an $\mathrm{OASPL_{Max}}$ of 113 dB. Later, Guest and Jones (1967) used the same model to produce a map of predicted Saturn-V $\mathrm{OASPL_{Max}}$ beyond KSC. Because their map has relatively low resolution, the map has been redrawn with a satellite image background in Fig. 4. The map's noncircular asymmetry stems from it being a composite of maximum predicted levels from launches originating from any one of the Launch Complex (LC) 39 pads, including LC-39C, which was never built. According to this model, $\mathrm{OASPL_{Max}}$ at the Vehicle Assembly Building (VAB) was 124–125 dB and 105–110 dB at communities near KSC.

Equation (1) provides an additional opportunity to compare OAPWL and the measured and modeled $\mathrm{OASPL_{Max}}$ for the Saturn V. Assuming an OAPWL of 204 dB re 1 pW, a maximum emission angle of 65° relative to the plume, and the horizontal ranges in Fig. 3, Eq. (1) results in a predicted $\mathrm{OASPL_{Max}}$ of 162.0, 154.9, and 148.9 dB at the distances used in Fig. 3. These levels are within $\sim$3 dB of the Saturn-V measured OASPLs in the legend of Fig. 3, strengthening the physicality of the range of Saturn-V OAPWL and $\mathrm{OASPL_{Max}}$ values given in this article. To pick a far-field location outside of KSC for an additional comparison, the Space Coast Regional Airport is at a distance of 21.6 km

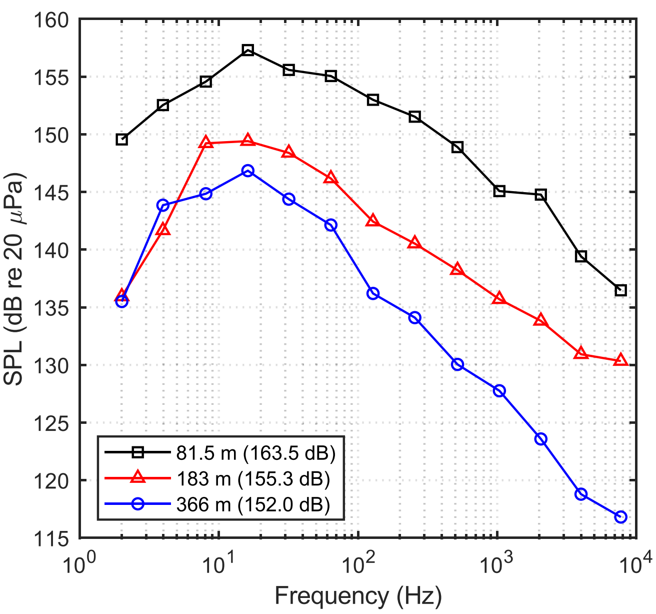

FIG. 3. (Color online) Octave-band sound pressure level spectra from a Saturn-V launch based on data digitized from Fig. 7 of McInerny (1992). The radial distance from the vehicle and OASPL calculated from each spectrum are reported. Each spectrum is the decibel average of two measurements made at approximately the same distance.

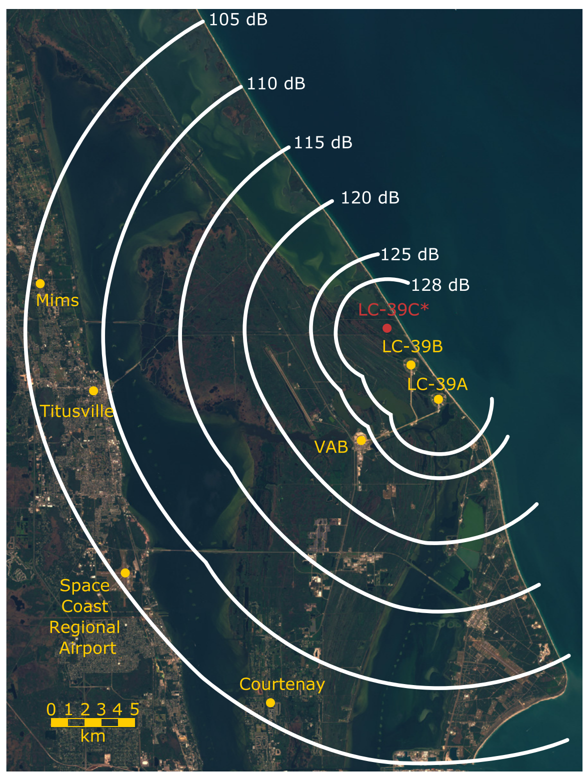

FIG. 4. (Color online) The predicted maximum OASPL map for Saturn-V launches, adapted from Fig. 20 of Guest and Jones (1967). Contours are a composite prediction for launches from each of the three originally proposed Saturn launch complexes. LC-39C (shown with an asterisk) was never built.

from LC-39B. Using Eq. (1) and the same assumed parameters, the predicted $OASPL_{Max}$ is 113.5 dB, whereas the prediction by Guest and Jones (1967) is around 106 dB. Although Eq. (1) is considerably simpler than the model by Wilhold *et al.* (1963), the reasons for this discrepancy are unclear, and no measured levels are available for comparison. Nonetheless, the two values provide some estimate of the range of levels that were expected of the Saturn V in the surrounding communities.

B. Peak sound pressure levels

The instantaneous peak sound pressure levels for the Saturn V can be estimated by leveraging knowledge of the crest factor for supersonic jets, the difference in decibels between peak level and time-averaged level, for heated, supersonic jets. Whereas a sinusoidal signal has a crest factor of 3 dB, Gaussian random noise results in a crest factor of 13–14 dB. However, the pressure waveform probability density function for rockets (e.g., McInerny, 1996b; Gee *et al.*, 2009) and high-power military jet aircraft (e.g., Gabrielson *et al.*, 2005; Gee *et al.*, 2016) is non-Gaussian and positively skewed, i.e., with larger-amplitude compressions than rarefactions. Consequently, the crest factor approaches 20 dB (Gabrielson *et al.*, 2005) with 18 dB typical in the near field (Gee *et al.*, 2014). In the far field, crest factors approach those of Gaussian noise as large-amplitude compressions form propagating shocks that are nonlinearly attenuated more quickly than lower-amplitude waveform segments, thereby reducing the pressure distribution's skewness.

What does this mean for the Saturn-V peak levels? Assuming an 18 dB near-field crest factor, the peak pressure levels at 81 m (9.6 $D_{e,\mathrm{eff}}$ from the centerline) were approximately 182 dB, which corresponds to a peak pressure of 25 kPa or about 25% of sea-level atmospheric pressure. While this peak level represents acoustic amplitudes that would propagate nonlinearly to rapidly form shocks and result in perception of jet "crackle" (e.g., see Gee *et al.*, 2016), will it melt concrete or set grass or one's hair on fire? It will definitely not. Giraud *et al.* (2010) provided an expression for the acoustic temperature variation in terms of acoustic pressure and evaluated it with rocket noise. According to their Eq. (2), a 25 kPa peak pressure in air results in a peak temperature increase of nearly 21 °C (38 °F). While this is a large increase for a sound wave, its modest magnitude, the rapidity of acoustic heating and cooling, and typical objects' thermal inertia mean that this is far from causing combustion. If reports were accurate, combustion likely resulted from the plume or the dispersal of highly heated debris. "Melting" of concrete could have been spallation caused by plume impingement, possibly enhanced by rapid evaporation of water from deluge systems or rain absorbed by the porous concrete.

Returning to the topic of crackle and peak levels, some have claimed that crackle in rocket noise is caused by the clipping of the sound wave by a temporary vacuum. This is false. While this article cannot describe what happens very near the plume's shear layer, in the far field, where crackle is heard and felt by observers, the Saturn-V pressure rarefactions are nowhere close to vacuum. Although subjective studies have only been performed for military jet engine exhausts and not rockets, crackle perception has been definitively shown to be tied to the generation and nonlinear acoustic propagation of shocks (Gee *et al.*, 2018, and references within).

VI. CONCLUSION

This article has discussed acoustic levels from historic Saturn-V launches: overall sound power, maximum overall sound pressure, and peak pressure. Measured overall power and pressure levels have been connected through an assumed acoustic efficiency of 0.5% and a peak directivity index of 8 dB. Peak levels have been estimated through understanding crest factors from modern measurements of military aircraft and rockets. Ultimately, while the Saturn V is wholly deserving of the awe it inspires as a symbol of what humanity can achieve, its acoustical reputation among Redditors and other well-meaning individuals is largely unfounded. Hopefully, this article and supplementary[1] homework exercises are useful resources for educators, aerospace aficionados, and others.

[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0013216 for Saturn V-inspired homework problems.

[2]See https://www.hq.nasa.gov/alsj/ApolloSpacecrftSystmsFAM67.pdf (Last viewed July 20, 2022).

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